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ROCHESTER INSTITUTE OF TECHNOLOGY

IMPLEMENTATION OF AN OBJECT-ORIENTED LIFE CYCLE ASSESSMENT

FRAMEWORK USING FUNCTIONAL ANALYSIS AND SYSTEMS ENGINEERING

PRINCIPLES

By

Shantanu Avinash Gadre

Submitted in Partial Fulfillment

of the Requirements for the Degree of

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DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

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CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

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thesis requirements for the

Master of Science degree

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ABSTRACT

There has been a growing awareness about the environmental impacts of producing and consuming goods and services. Among the various tools that have been developed to better understand these impacts, Life Cycle Assessment (LCA) is one of the most commonly used tools to estimate the environmental effects of products and services. Given that a significant percentage of a product's impacts are defined during the design and development, it is necessary to effectively integrate LCA into these early phases of the product lifecycle. However, the lack of standardized practices, complex modelling approaches, data and time requirements, special training requirements for designers, and uncertainties in the results make it difficult to apply LCA in the design and development stages. In order to integrate LCA into the design and development stage, it is necessary to systematically generate and compare alternatives, to analyze scenarios, and to evaluate changes for different product structures and architectures so that impacts can be minimized. Functional analysis is a widely-used technique in the conceptual design environment but it has not been effectively used in the LCA domain. In this thesis, functional analysis and systems engineering principles are used to implement an Object-Oriented framework for LCA. The results of the process demonstrate the potential for an easy to update and scalable LCA model that facilitates comparability. Each module in this model can be developed separately and integrated effectively into a larger model. This framework hold promise to better integrate LCA into the design and development phases.

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1.0 Background

1.1 Life Cycle Assessment (LCA)

There has been a growing awareness about the environmental impacts of producing and consuming goods and services. Among the various tools that have been developed to better understand these impacts, Life Cycle Assessment (LCA) is one of the most commonly used tools to estimate the environmental effects of products and services (Walter Klöpffer 2014). LCA is a systematic way to account for and subsequently manage the environmental impacts associated with the entire life cycle of the system under consideration.

Life Cycle Assessment is defined by ISO 14040 (ISO. 2006) as “*LCA studies the environmental aspects and potential impacts throughout a product’s life cycle (i.e. cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impact needing consideration include resource use, human health, and ecological consequences.*” One of the important features of LCA is the capability to study the product throughout its entire life cycle. The ‘cradle to grave’ approach ensures that all the stages of a product’s life cycle are considered for assessing its environmental impacts. A product’s life cycle is composed of different unit processes namely raw material extraction, production of intermediate products, production of end product, usage of product by a consumer and its disposal or/and recycling. Even the transportation across these phases is taken into account in an LCA study (Walter Klöpffer 2014).

An important concept used in LCA is the functional unit. The functional unit is defined by ISO as “the quantified performance of a product system for use as a reference unit”(ISO. 2006). It allows for comparison of product systems satisfying the same or similar purposes. Hence the functional unit is key for comparing LCA results. According to the ISO 14040 LCA shall include the following phases, as illustrated in Figure 1: Phases of Life Cycle Assessment (ISO. 2006)

1. The Goal and Scope Definition phase-

This section includes the selection of system boundaries, functional unit definition to be used, allocation procedures, assumptions and limitations, impact categories to be analyzed and interpretation methods. It is an iterative process since various aspects of the scope may change to meet the original scope of the study.

2. The Inventory Analysis phase-

This is an inventory of the input/output flows of the system under study. Collection, quantification and allocation of data are of key importance for this phase. This process is also iterative since the more the product is analyzed, the more is learned.

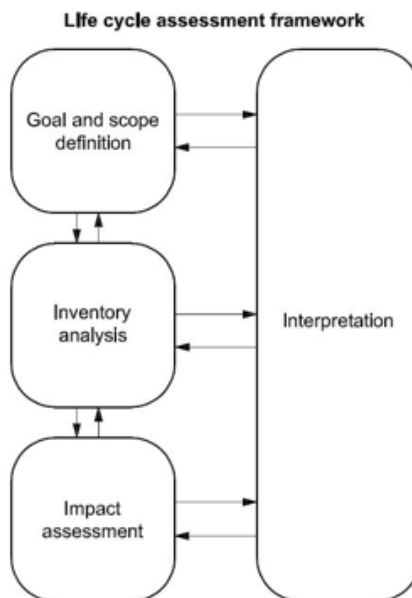


Figure 1: Phases of Life Cycle Assessment (ISO. 2006)

3. The Impact Assessment phase-

In this phase, the environmental impacts of each life cycle phase are evaluated. The results obtained from the previous section are needed to perform this assessment and data is related to specific impact categories and indicators, as defined in the first phase and aligned with the scope of study.

4. The Interpretation phase-

The final phase of a LCA study summarizes and discusses the findings, obtaining conclusions and making further recommendations for the system.

The direct applications of LCA as mentioned in ISO 14040 include product development, strategic planning, public policy making and marketing.

Following are some of the strengths of LCA mentioned by Marry Ann Curran (Walter Klöpffer 2014) -

1. Comprehensive assessment- Life cycle assessment is a 'cradle to grave' approach that helps in evaluation of environmental impacts associated with all of the Life cycle stages of the product.
2. Highlighting environmental tradeoffs- LCA assists in the identification of tradeoffs that occur due to changes made to the system.
3. Structure for investigation- The ISO standards developed (ISO 14040) provide a general framework to conduct an investigation in four phases.
4. Ability to challenge conventional wisdom- LCA provides the data and information with which what is considered environmentally friendly can be questioned
5. Fosters communication and discourse- the LCA methodology has evolved as a basis to communicate the overall performance of products and services.

On the other hand a two part study pointed out 15 different issues and limitation that related to all of the phases in LCA (Reap et al. 2008). After assessing the severity of the problems and the solutions available the authors rated these problems and identified five critical areas which in their opinion require attention. These areas provide an overview for researchers to direct their efforts.

1. Functional Unit Definition – affects goal and scope

Appropriate selection of the functional unit is critical because different functional units may lead to different results for the same product system. Multiple errors could occur while identifying functions,

defining functional unit and defining reference flows resulting in an inaccurate representation of product system.

2. System Boundary Selection – affects goal and scope

Activities and processes to be included in the LCA study are determined by system boundary selection.

“Boundary selection is influenced by product system’s unit processes, included life cycle stages, impacted geographic area and relevant time horizon”(Reap et al. 2008). Appropriate selection of these boundaries requires large amount of data, time and costs with very little or no value added. Currently there are no clear practical guidelines and tools to support boundary selection.

3. Allocation – affects the inventory phase

Allocation refers to the assignment of environmental burdens of multifunctional process amongst its products or processes. There are various proposed solutions to tackle this issue but unfortunately there is no single method that provides a general solution.

4. Spatial Variation – affects the impacts assessment phase

Unlike global impacts the regional or local impacts require spatial information for accurately associating the sources of impacts. Even though various methods have been developed to address this issue most assessments ignore spatial considerations.

5. Data availability and quality – affects all four phases

Poorly measured data, data gaps and proxy data are the main sources of uncertainty in LCA results. Also, the data for life cycle inventories is not widely available. Data collection costs can be very large. In many cases the data may be outdated as it is compiled at different time periods. Data may also be unrepresentative as it is taken from a similar but not identical process.

1.2 LCA in Product Development

Although one of the important applications of LCA is in the area of product development, it is difficult to use LCA during design phases due to the following reasons (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010):

- The process of conducting a LCA is very time consuming.
- LCA requires a lot of information which is usually not available during the design stages.
- The complex modelling approach used in LCA is not consistent with design models.
- Conducting LCA and analyzing its results requires special training.
- LCA results are always subjected to a certain level of uncertainty.

Practitioners have developed Streamline Life cycle assessment (SLCA) methods to address some of the limitations presented above (Todd et al. 1999). These methods are simple, quick and less expensive to execute. As covering all of the process is a complex task, practitioners decide what to include in the LCA study based on their judgement and needs. It is proposed that if one stage of life cycle is dominant then the other stages may be streamlined considering their relative importance. Two of the popular SLCA methods are The Pollution-Prevention (P2) Factors methodology and AT&T abridged life-cycle assessment. SLCA is not a very robust approach to apply during the design phase because it is very qualitative and subjective (Todd et al. 1999). These methods are less precise when compared to a complete LCA. Also, streamlining adds varying amounts of uncertainty to the results. Nevertheless, this approach may provide some initial guidance to the designers for choosing their focus areas.

(Yousnadj et al. 2014) argued that inherently LCA is not design oriented. It is designed to analyze the completely defined components and structures, but it cannot be used while deciding the product architecture or selecting certain set of components to satisfy the required functions. Also, the lack of correlation between the design parameters and environmental impacts makes it difficult for the designers to interpret results.

With the limitations of the current methodology, LCA cannot be used by designers as a decision support system. LCA should help the designers to systematically generate and compare different alternatives, evaluate changes, and arrive at different product structures and architectures. It is important to support the design phase since it is known that as much as 80% of a product's environmental impact is

defined during this phase (Bohm et al. 2010). Hence environmentally conscious product development is a key issue that needs to be implemented in early design phases.

As was identified above all of the important decisions that guide the process of conducting an LCA are made during the goal and scope definition phase. Lack of proper tools and guidelines for defining appropriate functional unit and establishing system boundaries during this phase is a crucial issue that needs to be addressed. It is also necessary to develop a LCA model that can act as a decision support system for designers by efficiently modeling and evaluating changes. For developing such a model, the issues of time and data requirement and complex modeling approach need to be dealt with.

In the remainder of this thesis, Chapter 2 will discuss the literature review which will focus on the following three areas: CAD-PLM-LCA integrated tools, Functional Analysis in LCA and Object orientation / Modularity in LCA. Chapter 3 will clearly define the problem statement. In Chapter 4 the methodology used to address the problem will be described with the help of a simple example. Chapter 5 will be dedicated to the details of a case study implementation. Chapter 6 will discuss the results and conclusions derived from the work. Chapter 7 will provide a discussion around the opportunities for the future work.

2.0 Literature Review

As it is seen in the previous section the use of LCA in the design phase is a challenging task. The efforts made to overcome this obstacle are presented in the literature review. The first section of the literature review concentrates on the CAD-PLM-LCA integrated systems. The second part presents the use of functional analysis in LCA and the third part discusses the efforts to introduce modularity/object orientation into the LCA to enhance its use in design phase.

2.1 CAD-PLM-LCA Integration Efforts

Introduction of Computer-aided design (CAD) and Product Lifecycle Management (PLM) systems have revolutionized the design process (Morbidoni et al. 2012). The efforts to integrate the CAD-PLM and LCA systems to help designers develop eco-friendly products are reviewed in this section.

Jean-pierre Theret et al. (2011) explore the possibility to connect the design tools like CAD and PLM with environmental assessment tools such as LCA, so as to deliver products with lower environmental impacts. It is proposed that the development of an Environmental Data Workbench (EDW) will address the issue of sharing information during the design phase between the various stakeholders, as well as enhance the analysis of different business scenarios like compliance, declaration and eco-design. The concepts of BOS (Bill of Substances) and BOP (Bill of processes) are two new concepts that are introduced in this paper. Bill of substances is the extension of Bill of Material to include the chemical composition of materials in order to get the weight of all chemical substances used in the product. Bill of processes is used to describe the transformation processes in terms of input and output flows along the entire product life cycle. The innovative part is the use of the Product-Process-Resource (PPR) model for all of the Bill of Processes. The impacts are calculated based on the resources required for each process. The model is shown in the Figure 2.

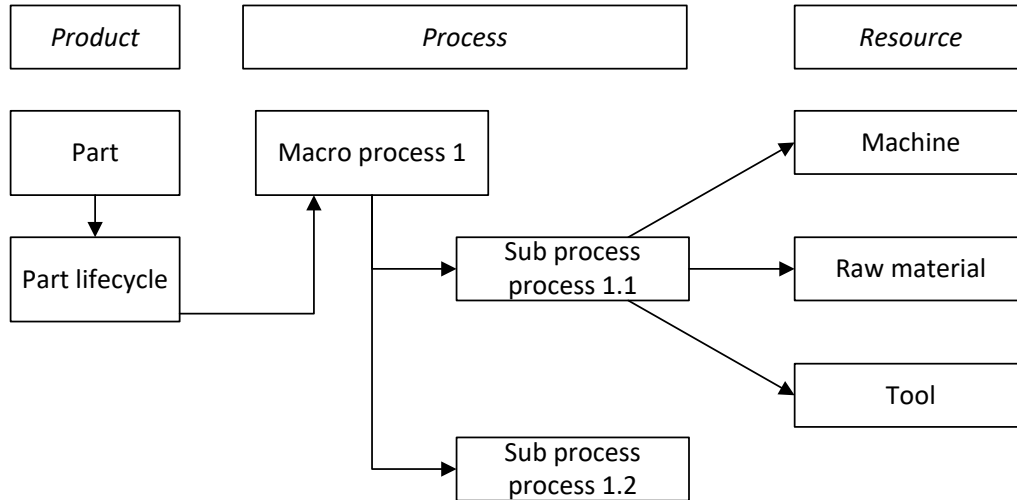


Figure 2: PPR model - adapted from JP Theret, Evrard, and Mathieux (2011)

The EDW acts as a hub for collecting the data from CAD, CAE and PLM systems. It then validates the data and publishes the results with the help of environmental analysis applications like openLCA. The research work provides a tool that can assist in evaluating impacts of products defined in CAD-PLM systems, but it fails to demonstrate how the different solutions generated will be compared. It does not mention the way in which knowledge in the system will be reused to evaluate new designs. Only those designs that are completely defined in the CAD-PLM system can be assessed. An important limitation of the EDW as mentioned in (Yousnadj et al. 2014) is the decontextualized environmental data link between the environmental results and the design parameters is lost.

Fabrice and Lionel (2007) present a framework to extract product data such as, product architecture, part details, energy details, and packaging details, from a shared CAD-PLM model. This information is then provided to a specialized environmental assessment tool that outputs the results in the form of life cycle assessment indicators like ozone depletion, global warming, toxic releases. The proposed platform is implemented using the PLM software SmarTeam and eco-design software EIME. After running some real-time cases it was found that if the PLM data is correctly parameterized, a greater amount of encapsulated information can be extracted as compared to CAD systems. The important conclusion is that PLM is a more flexible and promising option. One of the important limitations of the

study is that it did not explore how the environmental performance of design alternatives can be assessed to assist designers in making decisions. The usefulness of the tool is questionable when applied during the conceptual design phase where different options are evaluated by designers.

As mentioned above, in order to perform quick and easy analysis in the design phase simplified life cycle approaches have been developed. Morbidoni et al. (2012) attempt to connect SLCA tools with CAD tools to produce reliable environmental assessment results that can be visualized at an early design phase. The proposed framework consists of three modules, namely LCA software, CAD software and the user interface. The product structure and geometric information is extracted from the CAD models. The user interface allows the user to select the manufacturing processes, materials, the processes involved in the use phase and the end of life phase from an LCA database. An important feature is that the manufacturing processes are connected to the machine database of the company. This ensures that real process data is computed.

In order to facilitate comparison, results are displayed in form of graphs and data in the user interface. A case study was implemented on a washing machine and the results were obtained based on different life cycle phases. The results demonstrated that a ‘cradle to grave’ evaluation of product is possible by integrating SLCA and CAD systems. One of the major weaknesses of the tool is that it requires a lot of human intervention and increases the designer’s efforts. The framework only supports the detailed design phase.

Germani et al. (2013) proposed a new methodology for the designers with no specific knowledge of eco-design processes to develop sustainable products. A new software platform G.EN.ESI supports this methodology. In this methodology, some new steps are added to the traditional design process to address environmental constraints. The reengineered method consisting of six steps-

1. Functional Analysis
2. Initial assessment and determination of environmental hot spots

3. Determination of the environmental strategy and deployment in indicators (targets)
4. Guidance- Rules and guidelines
5. Sustainability check – LCA, LCC, specific modules and reports
6. Impact of the company decisions to the long-term company objective

In order to support the method, the software tools required are identified and integrated into a platform. The G.EN.ESI platform consists of the following modules- CAD-PLM module, lifecycle design module, supplier web portal, guidance module and report module. A case-based reasoning module (CBR) helps the designers to use existing knowledge and guidelines to improve products. The research does a good job in identifying and integrating different tools. It also does highlight that functional analysis is an important step in the design phase that helps to group components in modules and to define a functional unit, but the software platform developed does not support functional analysis. In addition, there is no guidance to connect the functionality, reference flows, and design parameters with the impact indicators.

In order to allow designers to consider environmental issues during early design phases Yousnadj et al. (2014) attempt to connect SLCA and PLM. A four-step methodology is proposed and a system architecture is developed by this research.

1. Planning- Establishes the objective and scope of the study. It also applies LCA to some completely defined products that will serve as a reference to identify relevant Life cycle stages.
2. Definition of Required elements- Specifies the level of information required for conducting the LCA. It limits the data required and helps to structure results and indicators. It is proposed that results be stored in PLM.
3. System specification and development- Defines functional and technical specifications for the PLM.
4. Deployment of eco-design- Just the creation of an eco-design tool is not enough. It is necessary to ensure that the design processes are aligned with the tool.

This methodology has been implemented by using Teamcenter PLM system of Siemens and SLCA. The researchers claim that one of the prominent aspects of this methodology is that it keeps the links between the environmental impacts and its sources in the product characteristics. But this platform is still under development and it has not been validated. Also, no attempt has been made to remove the uncertainties inherent in the LCA process that hinder its application in design.

Ostad-Ahmad-Ghorabi et al. (2009) present the efforts to develop a tool that links CAD-LCA for environmental assessment in the early design phase. Extraction of information from previous models for performing assessment of new products is an important aspect of the approach. The concept of Life cycle families is introduced, so that a full scale LCA of new products is not needed. Life cycle families contain parametric models of products which share common behavior. A reference value for comparison is set which is the best in class scenario. The new concept is compared to this reference value to assess if the product is performing better or worse. The following three steps summarize their approach: (1) Perform LCAs of existing products and store the results in the CAD system (2) Develop the LCA family database in form of parametric descriptions (3) Comparative evaluation of a new concept.

A case study was implemented with a crane manufacturing company to test the approach. The project was successful in terms of demonstrating a way to reuse previous knowledge in the CAD system for quick evaluation of new concepts, however the static nature of the LCA family database is a major shortcoming of the implementation. The LCA family is dynamic and growing and depends on the product under investigation. Also, the accuracy of defining the LCA family and its parameters will directly affect the accuracy of the LCA results. The establishment of product families is based on the Fun theory (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010) that itself has various limitations that will be discussed below.

The need for a tool that can support the evaluation of alternative design concepts is presented in (Morbidoni et al. 2010). The Computer-aided life cycle inventory (CALCI) tool developed is an interface

between the PLM system components and LCA software to facilitate quick and efficient data retrieval. The bidirectional link between PLM-CALCI helps to extract the product structure i.e. processes associated with components and allocation parameters. A user interface is used to relate the data from the LCA and PLM software platforms. A prototype is implemented in the form of a test bed, only the Mechanical Computer Aided Design (MCAD) module of PLM system is used (solid edge) and it is interfaced with the openLCA package. Different design solutions of a telescopic desk lamp were chosen for evaluation and the results were presented in graphical form. The tool helped to identify components with higher environmental impacts. The main advantages of the tool developed are speed of compilation, association of product design parameters with LCI parameters and immediate evaluation of design changes. The omission of usage, transportation and end of life phases from the product evaluation is a major drawback of the tool.

One of the major shortcomings of all of the CAD-PLM integrated tools discussed above is the lack of support for the conceptual design phase. This phase of design is dominated by techniques like functional analysis. In any product development stage, functional analysis plays a key part in the selection of technologies/solutions, finalizing product architecture and building of new design concepts.

2.2 Functional Analysis in LCA

“Functional analysis is a technique that helps to describe the functionality of the system in an abstract manner without relying on the physical structure. This kind of representation allows for more degree of openness when generating solutions” (Otto and Wood 1998). Developing product architectures and function structure generation are important applications of functional design. In this section, the efforts made to highlight the importance of functional analysis in the conceptual design environment for developing products with least environmental consequences will be discussed.

Haapala, et al. (2011) tackle the issue by automating concept generation using design repositories and integrating them with LCA. The design repository used for generation of concepts contains

information on artifact function, failure, physical parameters, performance models, sensory information and media for over 130 electro-mechanical products. In this methodology, functional modelling is used to describe the product in the form of flows of material, energy and information. This functionally decomposed model is supplied to the automatic concept generator that creates different concepts based on each function. A ‘cradle to gate’ impact evaluation of these concepts is performed by comparing them with similar functionality models stored in the design repository. The results are then presented to the designers for selection and analysis.

While the method successfully presents the use of design repositories and concept generator for designing environmentally sound products, the method does not address a possible way to include use, transportation and end of life scenarios for evaluation. Also, the issue of the difficulty of comparing LCA results, particularly due to the lack of a standardized functional unit definition is not addressed.

Devanathan, et al. (2009) develop a novel semi quantitative tool, specifically for early design stages. An attempt is made to connect the functional data to the environmental impacts through the product structure. A new tool Function Impact Matrix (FIM) is introduced to achieve this. The FIM uses the information from the function-to-component mapping matrix to distribute the impacts across functions. This approach helps the designers to identify which functions are important from an environmental perspective. LCA results of the benchmarked products are integrated into the WKM so that they can be compared with new products. Along with the traditional function-to-component matrix the FIM is used to generate new concepts. In order to find the extent to which each component satisfies a particular function, percentage contributions need to be assigned. However, there is no specific method or guidance given on doing this. The impact values generated are specific to the function- structure combination under analysis and cannot be extended to other combinations.

The need to standardize functional unit definition for comparison of products is presented in Collado-Ruiz & Ostad-Ahmad-Ghorabi (2010). They use the concept of functional product descriptions

in engineering design to address this need. The authors present a concept they call a ‘Fuon’ that connects the functional behavior to the functional unit to allow scaling of results within the LCA. Parameters are used to define the Fuons that represent main function and enable scaling. These Fuons can be used to compare different products and also compare product concepts with the existing ones. The researchers demonstrate the idea by developing two Fuons, namely “Physical Container” and “Logistics-intensive Element”. The physical Container Fuon is shown in Figure 3. Their work establishes a link between design theory and LCA and as such it may help the implementation of LCA in early design phase. However, the research does not clarify the implementation strategy of the method for complex products and full scale LCA. An attempt to improve this work is presented below.


Name – Physical Container	
Description- Element that encloses partly or totally other physical elements, protecting them or isolating them from external environment	
 <pre> graph LR M1[M] --> Store[Store] Store -- M --> M2[M] </pre>	Flow diagram
Parameters- 1] Physical parameters- Volume contained, weight supported, Number of storages 2] Constraint parameters- Thermal max temp, Mechanical constraints, dimensional constraints	

Figure 3: Physical Container Fuon (*Adapted from Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010*)

A Systems engineering and functional analysis approach is used in (Esterman et al. 2012b) to standardize the definition of a functional unit and to identify system boundaries and reference flows. The systematic identification of system functionality helps to identify fundamental reference flows that are key to ensure comparability between LCAs. The method to identify the enclosing system and the interfacing system addresses the issue of system boundary definition. One of the key outcomes of the work is the decoupling of consumer behavior from the definition of the functional unit thus facilitating the

generation and comparison of multiple use scenarios based of consumer behavior. The proposed framework is shown in Figure 4.

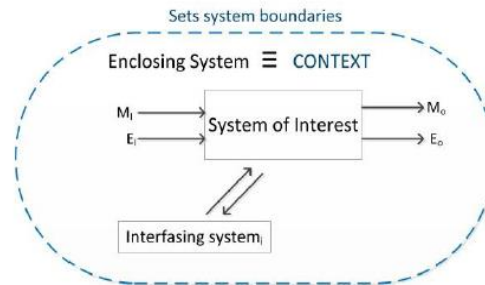


Figure 4: Generic LCA system framework (Esterman et al. 2012b), used with permission

A very exciting opportunity mentioned in this paper for the future work is the application of the same framework to the functionally decomposed system. “The application of the method to the sub functions will help in developing building block elements for LCA studies that can be integrated. This observation is important because it implies that the Object Oriented Paradigm can be applied to LCA” (Esterman et al. 2012a).

2.3 Modularity / Object Orientation and LCA

Modular products are defined as “machines, assemblies, or components that accomplish an overall function through a combination of distinct building blocks or modules”(Otto and Wood 1998). Two of the main advantages of modularity are standardization and re- configurability. In this section the importance of modularity when applied to LCA will be discussed.

Buxmann, Kistler, and Rebitzer (2009) propose a different approach for Life cycle assessment they term as ‘Modular LCA’. The approach starts with the concept of an Independent Information Module (IIM). Information modules are set up for each unit process or a combination of processes. At the core of the IIM are the ‘foreground processes’ which are the main processes under consideration for which data can be obtained and analyzed, e.g. main manufacturing process. Each foreground process is also

connected to a background data from generic processes like disposal and recycling. Thus, the extension of unit process with the input and output data based on reference flow forms a module. The work was focused on manufacturing processes and not products, hence the unit of analysis is a process. In this modular LCA approach all of the classification, characterization and assessment is done at the process level as opposed to conventional LCA where these steps are performed on the systems level after aggregation of all the data. One of the important advantages of this approach is the creation of reusable elements that can be integrated. In conventional LCA a later distinction between the data is not possible, this is not the case with Modular LCA.

The research explains this process considering only the manufacturing phase. The application of this approach to Product Development should be explored. A designer is interested in the technical design parameters which can be varied. If an LCA expert setting up the system identifies these parameters and defines the modules accordingly, then it will provide a direct decision support model. As the model is specifically targeted for designers it will reduce the dependency on LCA experts for making all of the decisions. The role of the LCA expert will be limited to defining new modules, the addition of parameters and for making major changes to the model.

In the eco-design area the focus of academia and industry is shifting from product improvement and product redesign to Alternate Function Fulfilment (AFF) and systems innovation. Recchioni et al. (2007) introduce the concept of modularity in product development to facilitate implementation of LCA in the early design phase. The researchers argue that in order to apply LCA to a modular system two characteristics will be of great importance namely 'Attribute Independence' and 'Process Independence'. Attribute independence suggests that the attributes of the parts in one module have less dependency on the parts of other modules. This allows for redesign of the module with minimum effect on other modules. Process independence means that the processes a module undergoes during its lifecycle are independent of the processes of other modules. This allows for redesign of process in isolation if a process change is made. An important outcome from the above considerations is that if the modifications are made to the

way a certain module satisfies its functions, these do not influence other modules and hence the Life cycle can be analyzed individually. This reduces the time and the data required for an LCA study and supports its application in early design stage.

The research does a good job in demonstrating the importance of modularity to aid in the application of LCA in the conceptual design stage. But the research does not provide a methodology to compare different modules that perform the same function. The work also neglects the use phase while comparing the modules, and it fails to present how the use parameters will affect the comparison. Also, the concept will hold true only if the connections between the modules are systematically established. It is important to find out how the life cycles of these modules integrate with the help of interfaces to form a complete product system.

Recently design synthesis tools have been developed to automate the process of developing complex products. These design synthesis tools generate a solution space that contains various alternative solutions to solve a given problem. Helms and Shea (2010) introduce an object-oriented principle to design synthesis tools to make them more flexible, intelligent and efficient. First, the research draws parallel between object orientation and design synthesis. Then it explains how graph grammar techniques can be used to implement the approach. The graph grammar captures design knowledge from various sources, for example a design catalogue, and then uses this knowledge to generate solutions. The authors explain that this process has various levels of abstraction/modularity and involves the reuse of knowledge, hence a class level structuring scheme is essential.

The object-oriented design synthesis has two parts: the definition phase and execution phase. The definition part consists of rules and vocabulary. Vocabulary is analogues to the class definition and rules are analogues to the functions in object orientation. The definition part is captured in a meta-model which defines modeling elements and valid combinations of elements. The meta model follows a hierarchical structure and also provides hierarchical inheritance. It can be envisioned that functional decomposition

along with the design parameters form the meta model. The actual execution is based on the rules and logic in the meta model. The execution operates with actual data objects.

The separation of the definition and execution phases enhances reusability of the meta-model for multiple applications and improves flexibility. It is important to note that different meta-models are comparable only if the naming conventions are followed i.e. a standardized approach is used for functional modeling. The concepts of this research provide a good guidance for developing an object-oriented LCA software.

3.0 Problem statement definition

After reviewing the different integration efforts to connect the CAD and PLM systems with LCA it can be concluded that these tools are helpful in the detailed design phase when the bill of material and the product structure is known, but they provide less assistance when it comes to supporting the conceptual design phase which is when the technologies are selected and the product architecture is developed. None of these tools effectively integrate the use of functional analysis during the design phase so as to aid in the generation and selection of solutions taking into consideration their environmental impacts. Also, many of the tools reviewed did not effectively address the lack of standardized processes to perform LCAs. Relative to the efforts to use functional analysis concept in LCA, the work of Esterman, et al. (2012a) is important because it gives a standardized methodology to integrate functional analysis with the LCA. Lastly, the literature was clear on the benefits of integrating modularity and object orientation into LCA, particularly to help in its integration into the early design environment.

The application of the framework presented in Esterman, et al. (2012a) to a functionally decomposed system is an important step toward the development of an object-orientated LCA platform. This this work will first, define a methodology to systematically apply the framework to a simple product that is used in our day-to-day life. Doing this will help further our understanding of the implementation details and challenges of this approach. Based on this understanding, improvements will be made to the

methodology and it will then be applied to a more complex electro-mechanical system. The implementation platform for the methodology will be SimaPro, which is a leading LCA software. While executing the methodology in a software environment, implementation issues will be identified and resolved. After the approach, has been implemented on the electro-mechanical product, the outcomes will be analyzed to understand the advantages and shortcomings of the approach. Finally, suggestions for improvements will be made and some guidance for the future work considering limitations of the current implementation will be provided.

4.0 Methodology

4.1 Methodology STEP 1: Functional decomposition and identification of reference flows

“Functional analysis is a technique that helps to describe the functionality of the system in an abstract manner without relying on the physical structure. This kind of representation allows for more degree of openness when generating solutions” (Otto and Wood 1998). The function of the product describes what the product is supposed to do, the function can be thought of as the reason for existence of product. Otto and Wood (1998) define a function as “A statement of clear, reproducible relationship between the available input and desired output of the product, independent of any particular form”. Usually the function is described by a ‘verb-noun’ pair. For example, the function of a hand dryer can be expressed as ‘Dry Hands’, similarly the function of printer can be expressed as ‘Print Documents’.

The main idea is abstraction i.e. ignoring the particular solutions and concentrating on generalization. Emphasize needs to be on ‘what’ is to be done rather than ‘how’ it is done. The black box shown in the Figure 5 is the basic construct used to implement this idea. It is called a black box as the purpose is known but the form is unknown. Material, energy and information are the three types of inputs and outputs for the black box modeling.



Figure 5: Black Box model, adapted from (Otto & Wood, 1998)

The overall function of the product can be divided into various sub functions. This is done by asking the question ‘how is the main function achieved’. The sub functions are the components or tasks that are necessary to satisfy the main function. The sub functions are also represented in the form of black box model i.e. the abstraction is still maintained. The sub functions can be decomposed further, by asking the same question ‘How is the sub function achieved’. For verification, it is important to ask the question ‘Why is the sub function performed’. The answer to why should be a higher order sub function. The ‘How-Why’ logic will lead to a structure of all the black boxes at different levels connected to each other known as a hierarchical function structure. This structure provides clear boundaries and at levels of similar abstraction and hence it is a very important tool for implementing object-orientation. This approach is known as hierarchical functional decomposition and is represented in the Figure 6.

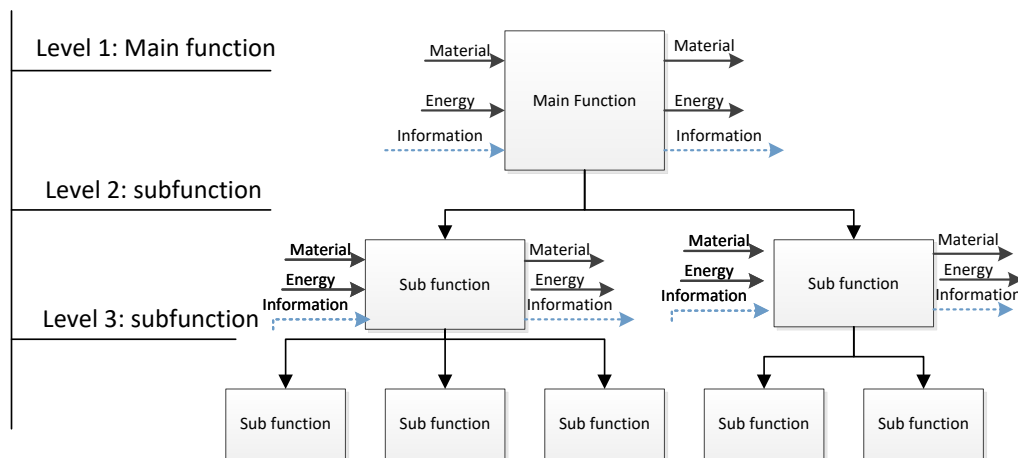


Figure 6: Hierarchical functional decomposition, adapted from (Otto & Wood, 1998)

The ‘verb-noun’ representation of a function does describe the purpose of existence of the product, but it was discovered through our experience that to support an object-oriented LCA approach it is helpful to represent the function in the form of the transformation of material, energy and information inputs into material, energy and information outputs. In practice, the predominate flows that are transferred are material followed by information. Since energy flows tend to be solution specific, they only tend to be a flow common to all systems if the purpose of the system is energy conversion.

Thus, the more comprehensive function descriptor that we adopt in this work is of the form ‘verb-noun pair-inputs’ to ‘verb noun pair-outputs’. For example, the function of the printer that was earlier expressed as ‘print documents’ can be expressed as ‘Mark Media to Print Documents’. While clearly there are energy inputs into this system, they are not shown in Figure 7 because they are specific to the technological solution and hence not considered to be a flow common to all systems of this class.



Figure 7: Black box model of a Printer

The input flows for the system are the media (example –paper, cardstock), the marking materials (example -ink), the desired content and the output flow is the printed document. As discussed in the work (Esterman et al. 2012b) these reference flows are relevant to all the systems that satisfy this function and hence they help to establish a class of systems that are comparable. This same abstraction can be applied to all the levels as the system is decomposed further using a hierarchical functional decomposition approach. As we progress down the hierarchy, the abstraction levels decrease, the levels of detail increase and more decisions are made about the particular technological solutions that implement the

functions. Functional decomposition is an iterative process; assumptions are made from one level to the next.

The process discussed above is explained with the help of functional decomposition of a can opener. The can opener as the name suggests is used to open the can so that user can access contents inside the can. The main function in the black box form is shown in Figure 8.



Figure 8: Black box model of Can Opener

The material input into the black box is the can along with its contents and the lid. The information flow is the sealed state of the can. The material transformation leads to the separation of the lid from the can thus changing the state of the can from sealed to unsealed and allowing access to the contents. This main function along with the flows establishes a class of systems that can be used to make this transformation. Different types of can openers like the lever type, the rotating wheel type and even the electric can openers satisfy the same function mentioned above and lead to the same material and information transformations.

The question is then asked, “how is the main function, separate lid to access contents, achieved”? The answer to this question allows for the continued decomposition of the function structure into three sub-functions: access can, puncture can and rotate can. Note that even these second level functions are very generalized i.e. they are independent of any particular technology used to enable these transformations.

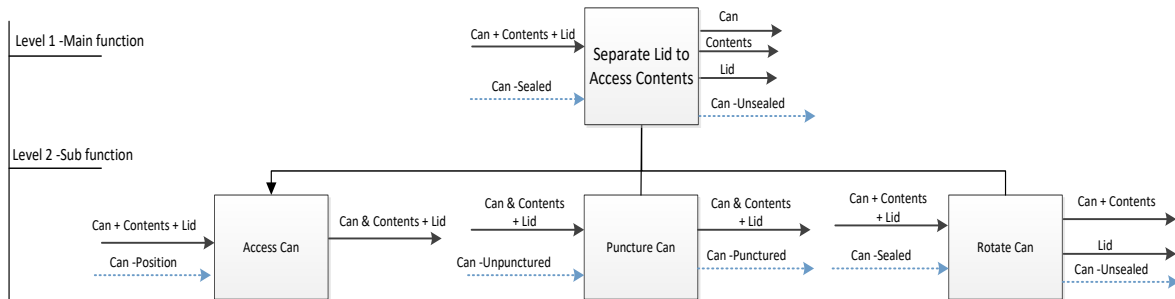


Figure 9:Level 2 sub functions of Can Opener

This same logic is applied to further decompose the second level sub-functions into third level sub-functions.

A) Access Can - In order to access the can, it first needs to be located so it can then be secured.

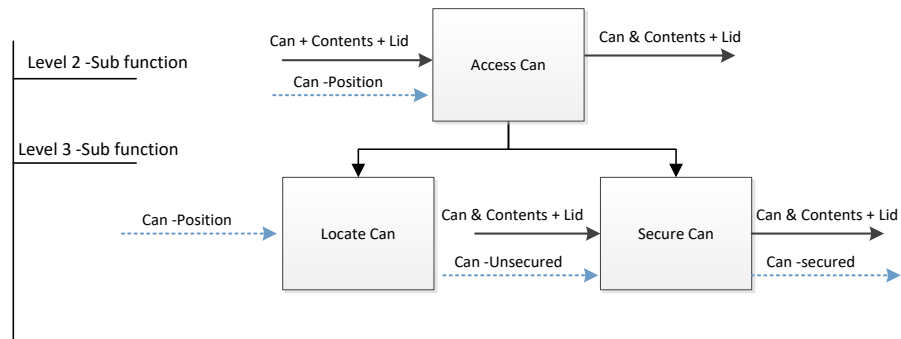


Figure 10: Access can decomposition

B) Puncture Can- The can is punctured by gripping the edge of the can and penetrating the lid.

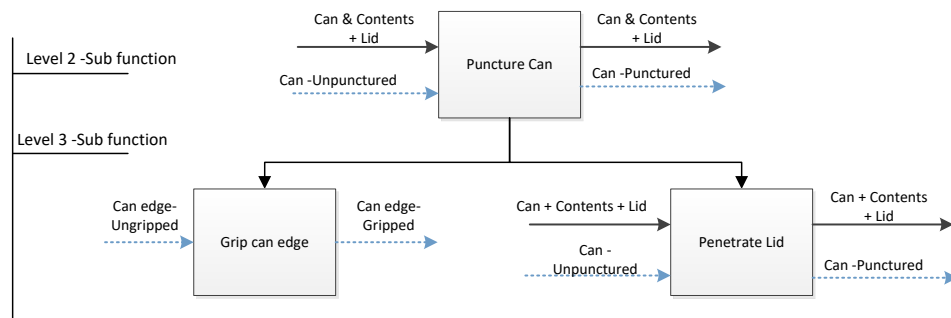


Figure 11: Puncture can decomposition

C] Rotate Can- Similarly, for rotating the can a torque must be applied and transmitted as well as restricting the linear motion of the can. When the can is rotated completely the lid is separated from the can thus changing the state of can to unsealed. Hence now the contents inside the can now be accessed.

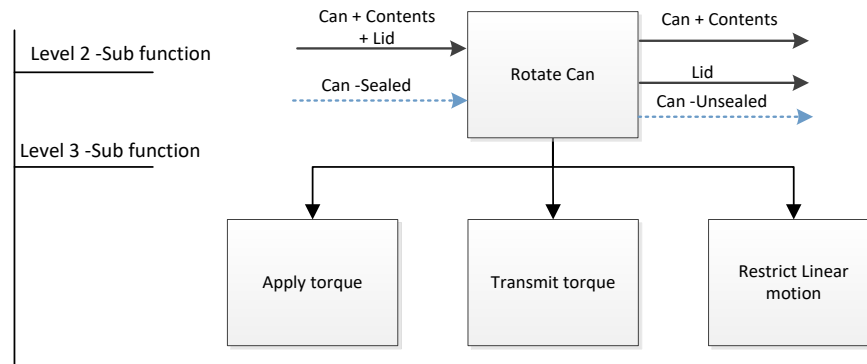


Figure 12: Rotate Can decomposition

The above structure generated can be verified by asking, “why is the function needed?” for each of the third level sub-functions and subsequently the second level sub-functions. This is an important step to ensure that the decomposition makes logical sense. Note that even though the third level of decomposition is still fairly general, decisions have been made about the solution, namely that it will be done through mechanically puncturing the can and then rotating the can itself. This is unavoidable and they key is to make these decisions in a controlled manner.

If taken to its logical conclusion, this How-Why logic will ultimately lead to the definition of components that fulfill very low level functions. Given the relative simplicity of the open can function, after the 3rd level a particular technological solution is, for all intents, defined. When that happens, a useful technique to ensure completeness of the function structure is to employ a bottom up approach. It will always be the case that if an LCA is to be executed a solution has to be defined. Thus, a reverse engineering method can be used that takes this into consideration. A detailed Bill of materials (BOM), which identifies all of the major and minor subassemblies, as well as the components, is generated from the defined solution. The basic, low-level functions of all the components should be noted in the BOM. It is also recommended that the features associated with these basic functions be identified.

The ‘bottoms-up’ reverse engineering approach that is implemented is called the ‘Subtract and Operate’ procedure (Otto and Wood 1998). The process is started by considering the most basic functions of components and features. The removal of each of these components and features is mentally simulated and thus the effects of operating the system without them can be deduced. From this, the functions of the components and the features can be established. These low-level functions can then be integrated into the top-down structure that was generated previously through the use of the how-why logic that was described above. There should be a reason for all of the components to be there and thus all of the solution specific sub-functions identified using this approach should roll up and map into the structure generated using the ‘top-down’ approach. Any components, features and lower level sub functions that cannot be mapped expose the gaps in the function structure. To close these gaps either new higher level functions need to be identified or the existing functions need to be rearranged.

For illustration purposes, a simple butterfly can opener, which is shown in Figure 13, was used. First the user locates and grips the can manually. A small notch is made initially into the lid by applying the force to the main arm, which gets transmitted to the cutting blade. As the user turns the handle the can is rotated so that the blade continues cutting along the circumference of the lid until it gets separated from the can.

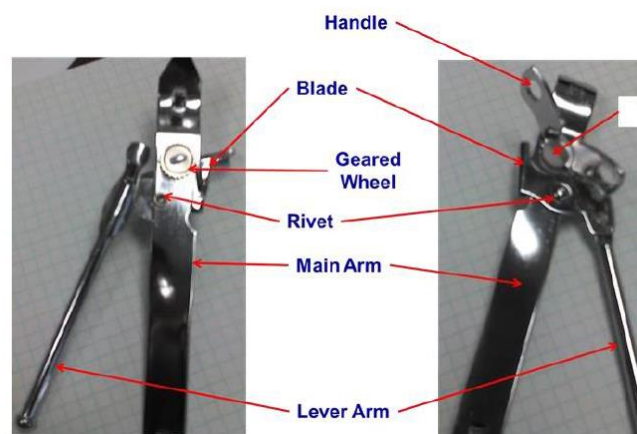


Figure 13: Butterfly Can opener

The next step is to develop a Bill of Materials as shown in Figure 14. Note that as this is a simple device no subassemblies were present. Appropriate engineering assumptions have been made with respect to material and manufacturing processes for parts.

Part Number	Part	Quantity	Material	Function	Part Features	Part Weight(gms)	Manufacturing Processes Used
1	Handle	1	MS	Enable application of rotational force		100	Forging
2	Blade	1	Stainless Steel	Create Notch		25	Machining
3	Feed/Gear Wheel	1	Stainless Steel	Transmit Torque Restrict Linear motion	Circular Geometry	15	Machining
4	Rivet	1	MS	Allow Rotational DOF		5	Forging
5	Main Arm	1	MS	Enable application of force		200	Forging
6	Lever Arm	1	MS	Enable application of force		175	Forging

Figure 14: BOM-Can opener

In order to understand the basic functions of these parts the operation of can opener with removal of these parts is mentally simulated. For example, if the main arm is removed then the force required to penetrate the lid of the can cannot be generated. Similarly, the blade is removed the lid would not be penetrated. Once these basic functions are understood the question of which higher level functions are supported by these basic functions is addressed. For example, ‘creating a notch’ and ‘applying cutting force’ are essential to perform the higher-level function ‘Penetrate Lid’ which identified earlier in the top-down approach. Hence these basic functions are added to the top-down decomposition generated earlier and the respective components and features are mapped to the low-level functions as shown in Figure 15. The final function structure of can opener is shown in Figure 16 (Note- Flows are not shown in figure due to space constraints).

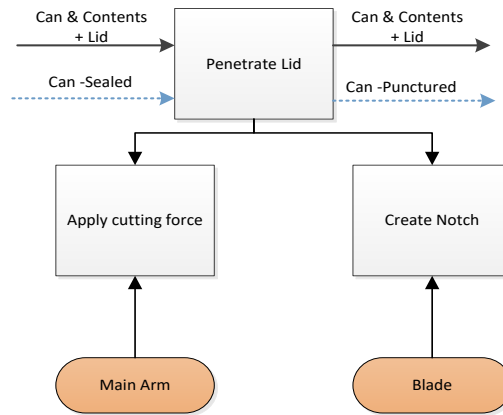


Figure 15: Structure mapping -penetrate lid

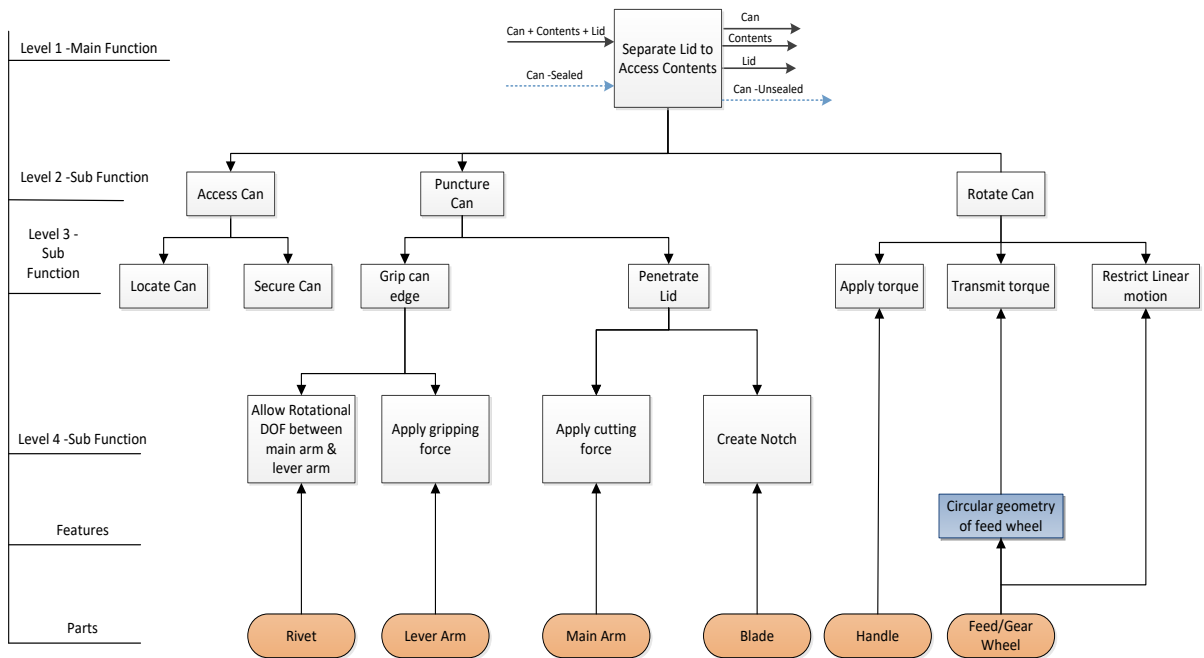


Figure 16: Function- Structure diagram of Can opener

4.2 Methodology STEP 2: Establish Use parameters, System parameters and Cumulative Damage Function (CDF)

As mentioned in the previous section, the main function is represented in the form of a transformation of material inputs to outputs that is independent of the technology implemented. The reference flows that were identified for the main function act as a guide to define the use parameters of

the system that implements this function and system parameters for the subsequent implementation of the sub-functions that support the main function. The use parameters are used to model the user behavior. The use parameters identified are not specific to any particular technology as they are derived from the reference flows. Changes in the consumer pattern can be modeled by changing the values and combinations of the use parameters.

For the can opener the main input flow of material is the can itself along with the contents and lid. The user selects the type of can that needs to open, hence type of can is an important use parameter. Associated with the type of a can is information like the can diameter, lid thickness and material properties of the can. Another important part of the user behavior is the frequency of use of the can opener. Some users may use the can opener very frequently while the other may not. To model this another parameter, number of cans, is defined. Thus, two use parameters for the main function pierce can to separate lid are- 1] Number of cans 2] Type of can (Diameter, Lid thickness, Material).

These use parameters further act as an input to determine the system parameters for the sub-functions. Each sub-function is considered as an independent system, hence the parameters that are used to define the behavior of the sub-functions are called as system parameters. It is important to establish the relationship between the use parameters and the system parameters. Once relationships are in place the changes to the use patterns will be automatically translated into the changes in system parameters at the lower levels. This will help to guide the selection of technological solutions based on user behavior. Note that if the sub-functions were stand-alone subsystems, what are referred to as system parameters become use parameters.

As discussed above, the main function of can opener is decomposed into access can, rotate can and puncture can. Currently the access can function is realized manually, so there is no particular technological solution to realize this function. As a result, there are no environmental impacts associated with the realization of this sub-function based on our current implementation. While the realization of this

sub-function is considered outside of the boundaries of our current model, it is important still to have this sub-function in the decomposition because in it necessary to accomplish the main function and in the future, it may be decided to satisfy this function through a technological solution like an intelligent can opener. The system parameters for the other two sub-functions and their relation with the use parameters are established as shown in the Table 1.

Table 1: Use & System parameters of Can opener

Main Function	Use Parameters – 1] Type of can (Diameter, Lid Thickness, Material) 2] Number of cans
Sub Function	System Parameters
A] Puncture Can	1] Puncture Force = f (Lid Thickness, Material) 2] Puncture depth= f (Lid Thickness) 3] Puncture cycles =f (Number of cans)
B] Rotate Can	1] Rotational force= f (Diameter, Material) 2] Rotation cycles = Number of cans

Consider the sub-function ‘Puncture Can’. The following three important decisions are to be made at the sub-functional level of ‘Puncture Can’.

1] What force should be applied to puncture the lid given the thickness of the can lid used by the user and the material properties of the can? The information required to determine this force can be obtained from the use parameter ‘Type of can’.

2] What should be the depth of the penetration? The depth of the penetration should be equal to the thickness of the lid and this information again can be obtained from use parameter ‘Type of can’.

3] Another crucial parameter is how many times does the puncture can function need to be activated? Every time a can needs to be opened the puncturing of the lid has to take place. Hence the number of puncture cycles is equal to the use parameter ‘number of cans’.

Now consider a scenario where in the user operates the can opener to open 200,000 cans during its life time. Hence the use parameter ‘Number of can’ is set to 200,000. It is further assumed that the user intends to open the same type of can with a thickness of 1mm, diameter of 120mm and having material constant Z (shear strength) = 2 N/mm². The information from this use scenario can be used directly to derive the three system parameters for ‘Puncture can’ using the following relationships. It was assumed that there exists an empirical formula to calculate the Puncture force.

$$Puncture\ Force = 25 \times Z \times Lid\ Thickness = 25 \times 2 \times 1 = 50N \quad (1)$$

$$Puncture\ Depth = Lid\ Thickness = 1mm \quad (2)$$

$$Puncture\ Cycles = Number\ of\ cans = 200000 \quad (3)$$

The system parameters for ‘Rotate Can’ sub function can be obtained similarly. ‘Puncture can’ and ‘Rotate can’ have been identified as two modules. The current research does not provide a method to identify independent subsystems from the functional block diagram. Modules/building blocks have been identified based on the separation of flows and the knowledge about the structure of solution. But the future work section does mention some of the approaches that can be used to address this.

The consumption of the system out of the total life of the system is based on usage pattern. This fraction of life consumed is calculate with the help of Cumulative Damage Function (Fumagalli 2012). The following equation explains the CDF -

$$CDF = Consumed\ Life / Limit (L_f, L_{obs}, L_{need}) \quad (4)$$

Consumed life- Represents use scenario under consideration

L_f = Limit due to failure

L_{obs} = Limit due to obsolescence

L_{need} = Limit due to lack of need of product

As a function of usage parameter, a certain life of the particular unit of interest will be consumed, this is main idea behind CDF. Thus, the CDF's can be calculated for each of the building block identified. We have already defined the relationships between the use parameters and system parameters which will help in scaling of the CDF's of individual building blocks based on usage. With change in user behavior the use parameters will change which will in turn drive changes to the system parameters which will further drive changes to the CDF values. Note- The details of the CDF determination methodology are presented in the work (Deo and Esterman 2016)..

Consider the can opener example, the 'Puncture Can' sub function is an individual building block. The following method is used to calculate the CDF of 'Puncture Can'. First, the operational stressors acting on the block is identified. Stressors are not defined that are specific to a particular technology, rather a class of stressors is developed, for example – Mechanical stressors, Electrical stressors etc. As a next step, a Failure mode effects and criticality analysis (FMECA) based on the functional decomposition is developed. This FMECA will help to identify the probable failure mechanism for the most critical component of the building block. It is concluded the FMECA that the most critical component fails by wear which leads to failure of entire functional block. Hence the models that can be used to calculate wear are explored. The most common model for wear is Archard's law which is given by

$$V = K \times F_n \times S \quad (5)$$

V- volume of material removed per operation

K-material constant

F_n = normal force

S= relative distance

Consider that V_{cr} is the critical volume of material lost before the function fails and N_{cr} is the critical number of operations for functional failure. Considering Archard's law the following relation can be established:

$$N_{cr} = \frac{K x F_n x S}{V_{cr}} \quad (6)$$

Out of the above parameters, the values of F_n and S can be derived based on the system parameters for 'Puncture can'. F_n is the normal force which is equal to the system parameter puncture force (50N), similarly the value of S is equal to the system parameter puncture depth (1mm). The other two parameters V_{cr} and K are dependent on technological solution employed. Suppose the supplier of the sub assembly provides us with this information V_{cr} (assumed to be 0.001 mm^3) and K (assumed to be 2 N/mm^2) or the information is derived from previous design knowledge, CDF can be calculated.

$$N_{cr} = \frac{2 x 50 x 1}{0.001} = 100000 \text{ units} \quad (7)$$

$$CDF = \frac{\text{Total number of operations}}{\text{Number of critical operations}} = \frac{\text{Number of cans}}{N_{cr}} = \frac{200000}{100000} = 2 \quad (8)$$

Thus, the details of the technological solution like its weight, geometry, bill of materials are not needed in order to compute the CDF. If the values of V_{cr} and K are available from standards or supplier data and the use parameters are known, then the calculations for CDF for 'Puncture Can' can be made. Thus, for any block once the use parameters and the critical solution dependent parameters are known the consumed life can be calculated. Once these relationships are established any changes can be modeled just by changes the values of the parameters.

The same approach to calculate the CDF of 'Rotate Can' was described above was used and its CDF also has a value two. Given the defined use scenario the two (CDF-puncture can) units of 'Puncture can' and two (CDF- rotate can) units of 'Rotate Can' are allocated to the main function of Separate Lid to Access contents as shown in Figure 17.

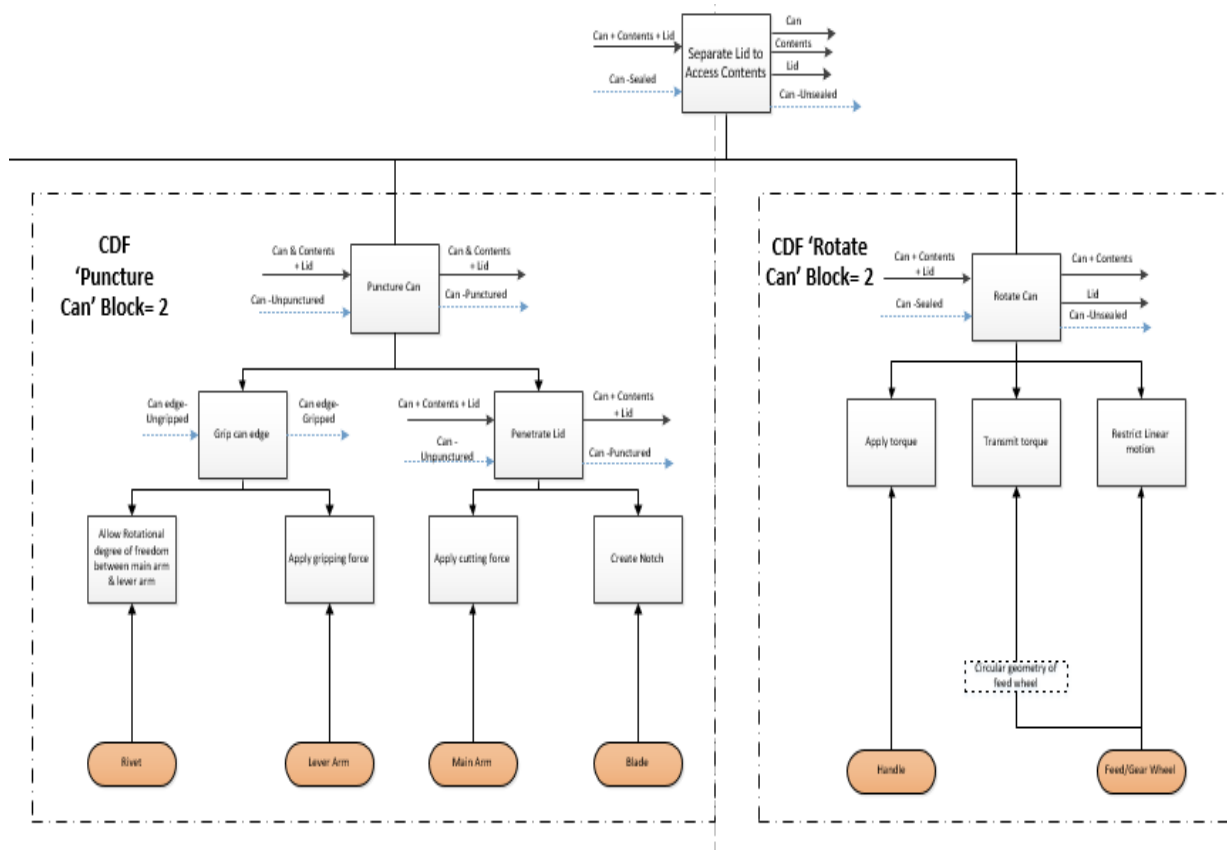


Figure 17: CDF allocation for Can opener

4.3 Methodology STEP 3: Implementation using SimaPro

SimaPro has been the world's leading LCA software package for 25 years. It is trusted by industry and academics in more than 80 countries. (About SimaPro, 2016).

In SimaPro product stages are used to construct the product under analysis. The Product is typically defined as a combination of different assemblies. Every assembly is constructed with the help of components. Each component is defined in terms of its material, weight and manufacturing process. SimaPro is designed to construct physical structure of the product, but not the architecture at the functional level. In our work the functions act as building blocks to create a hierarchical definition of product, which further connects to the structure. In order to overcome this limitation, dummy function blocks are defined under product stages. These functional blocks are then connected with each other

following the hierarchy of the functional decomposition developed earlier. An assembly named Function-Structure was created which consists of the functional decomposition of the can opener, refer to the Figure 18.

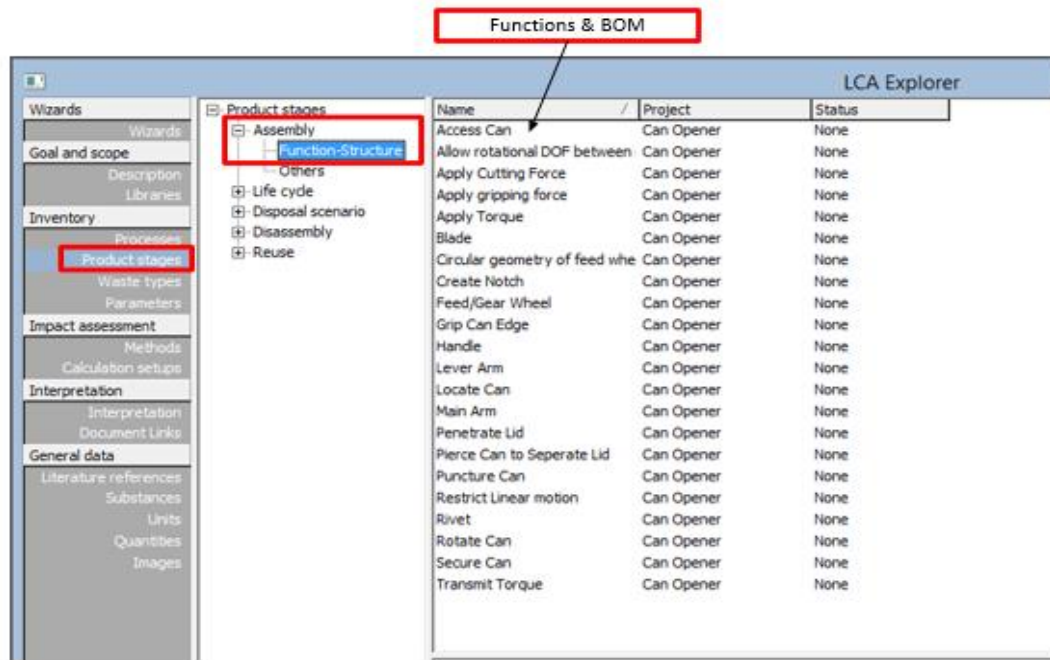


Figure 18: Can opener Function-Structure in SimaPro

Consider the first level of the decomposition where the main function is broken down into three sub functions.

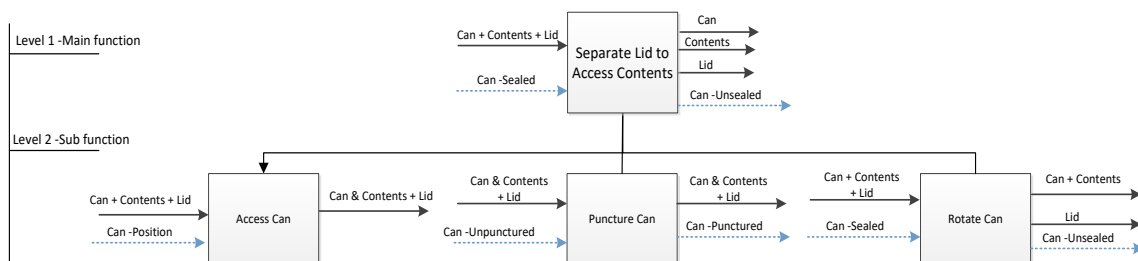


Figure 19: Level 1 to Level 2 decomposition



Name	Image	Comment
Seperate Lid to Access Contents		
Status	None	
Materials/Assemblies	Amount	Unit
Puncture Can	2	p
Rotate Can	2	p
(Insert line here)		
Processes	Amount	Unit

Figure 20: Building Blocks in SimaPro

In SimaPro the Materials/Assemblies section is used to define the subassemblies or the materials that constitute the part/main assembly. In our case, lower level functions are the building blocks for the upper level functions, hence they are added to the section Materials/Assemblies to form the higher-level functions. Thus Figure 20 implies that the ‘Separate Lid to Access Contents’ function is a combination of puncture can and rotate can (access can is outside system boundaries, hence not added). The amount of module allocated to the main function is dependent on the CDF of that module.

Consider the next level of decomposition in which the rotate can is further decomposed, which is represented in Figure 21 . One unit of apply torque, transmit torque and restrict linear motion is allocated to the rotate can function. Thus, the ratio of allocation is 1:1. But as seen earlier 2 units of rotate can module are allocated to the main function, hence when a function structure is formed two units of these three lower level functions will be allocated automatically.

Name	Image
Rotate Can	
Status	None
Materials/Assemblies	Amount
Apply Torque	1
Transmit Torque	1
Restrict Linear motion	1
(Insert line here)	

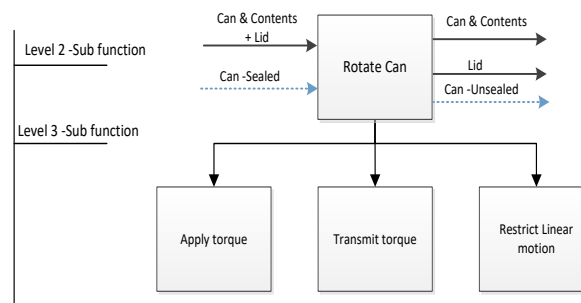
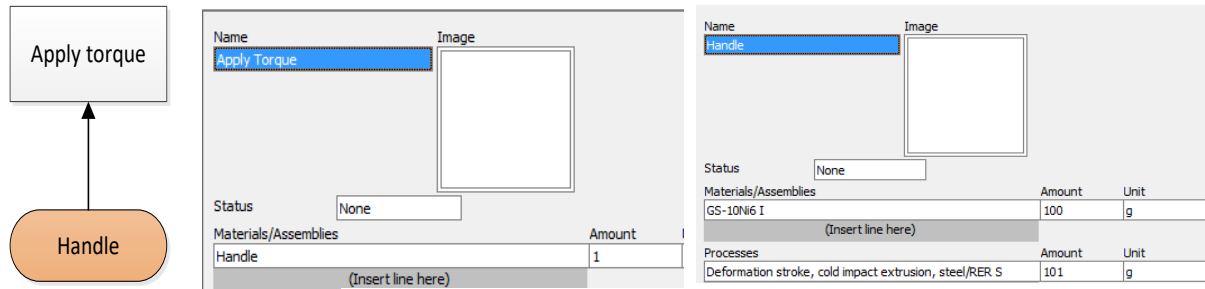


Figure 21: Rotate can implementation

Next the structure or the actual component is mapped to the lower level function. For example, the apply torque function is satisfied by the main handle. The main handle is defined in terms of its material, weight and the manufacturing process used as shown in the figure below. One unit of this main handle is then allocated to the Apply torque function. Note that the actual allocation of component to the main function is dependent on the CDF value of the module in which it is present.



Finally, we arrive at the final function-structure diagram which is shown in Figure 22.

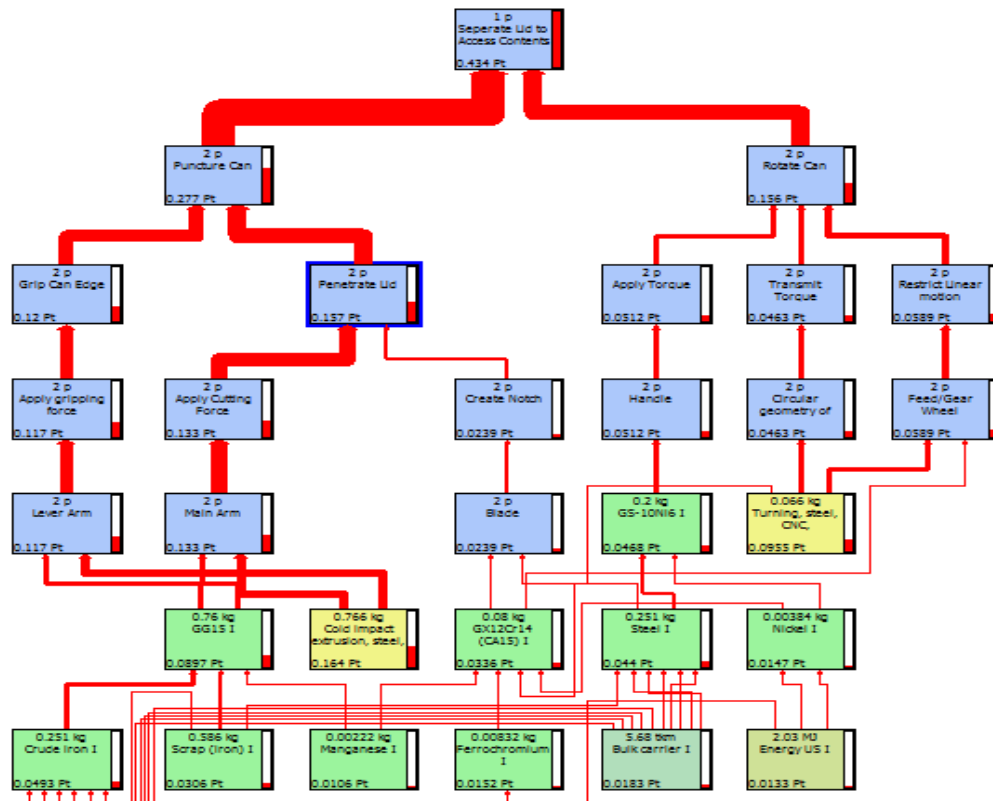
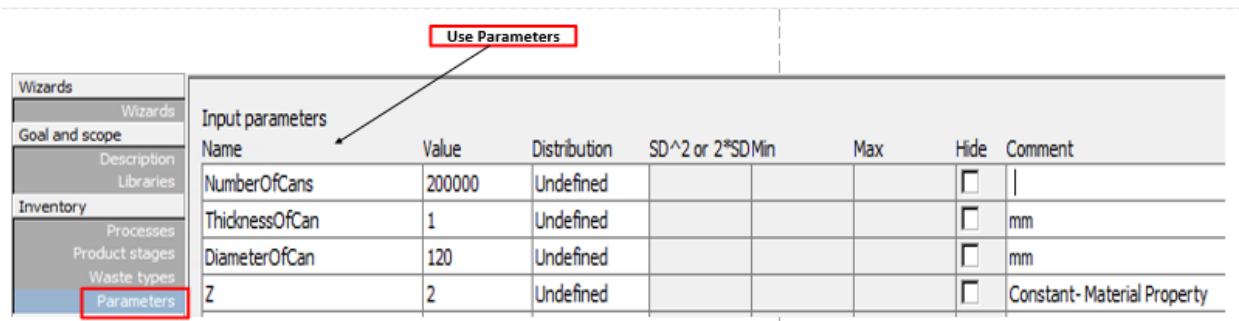


Figure 22: Can opener Function-Structure in SimaPro

In the following part use parameters, system parameters and the CDF calculations are set up. The use parameters which are derived from the reference flows of the main function act as the global parameters. These are defined in the parameters section under the inventory. The values of the use parameters are entered based on the use scenario. By changing these values different use scenarios can be constructed easily. These use parameters are accessible to any part of the system.



Use Parameters						
Input parameters						
Name	Value	Distribution	SD^2 or 2*SDMin	Max	Hide	Comment
NumberOfCans	200000	Undefined			<input type="checkbox"/>	
ThicknessOfCan	1	Undefined			<input type="checkbox"/>	mm
DiameterOfCan	120	Undefined			<input type="checkbox"/>	mm
Z	2	Undefined			<input type="checkbox"/>	Constant- Material Property

Figure 23: Use parameters for can opener in SimaPro

The next step is to calculate the system parameters and the CDF for the building blocks of the system. Consider the example of ‘Puncture Can’ in the Figure 24. Inside the parameters section of the assembly ‘Puncture Can’ two calculations are made. The system parameters are calculated based on the use parameters defined earlier. The formulas are defined in the Expression section. For calculating CDF, certain parameters like the V_{cr} and K which dependent on the solution employed are needed. These parameters which are either retrieved from supplier or from standard database are entered in the input parameter section. In the current implementation SimaPro does not prompt the user to enter the solution specific parameters based on the use scenario. In the future software platform, once the user parameters are defined and the system parameters are calculated the software should prompt the user to enter the solution specific parameters based on the derived values of system parameters.

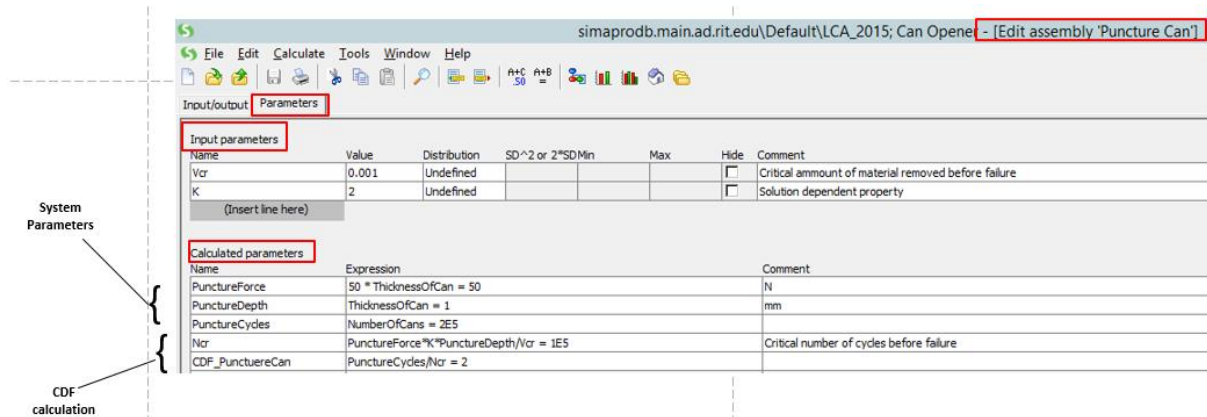


Figure 24: System parameters and CDF calculation for Puncture can

SimaPro does not allow for a formula/expression to be entered in the section 'amount' for allocation purpose, refer to the Figure 25. Hence in the current implementation once the CDF values are calculated for each module, these values need to be entered manually in the section 'amount'. The practitioner has to identify the level of abstraction at which the module is formed and mapped to a higher-level function, then allocate the amount based on the CDF value calculated. For example, based on the user parameters and the input parameters the CDF value for the 'Puncture Can' module was calculated by SimaPro as two, refer Figure 24. Based on the functional decomposition it was then identified that the 'Puncture Can' module maps into the higher-level function 'Separate Lid to Access Contents'. Then the value two (calculated CDF of 'Puncture Can') was entered manually in the amount section of the higher-level function as shown in Figure 25. In future software platform once the CDF value is calculated for the module, the amount of that module should be allocated automatically to the higher-level function it maps into, as the hierarchy of functions is already defined.

Name	Image		Comment				
Seperate Lid to Access Contents							
Status	None						
Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment	
Puncture Can	2	p	Undefined			= CDF_PunctureCan	
Rotate Can	2	p	Undefined			=CDF_PunctureCan	

Figure 25: Entering CDF values for allocation

Finally, we can analyze the impacts of the can opener for a given use scenario using the end point impact assessment. The end point impact assessment calculates the impacts on human health, ecology and resources. The red bars indicate the environmental load generated by each block. The thickness of the red line and the red bars help to identify the environmental hotspots.

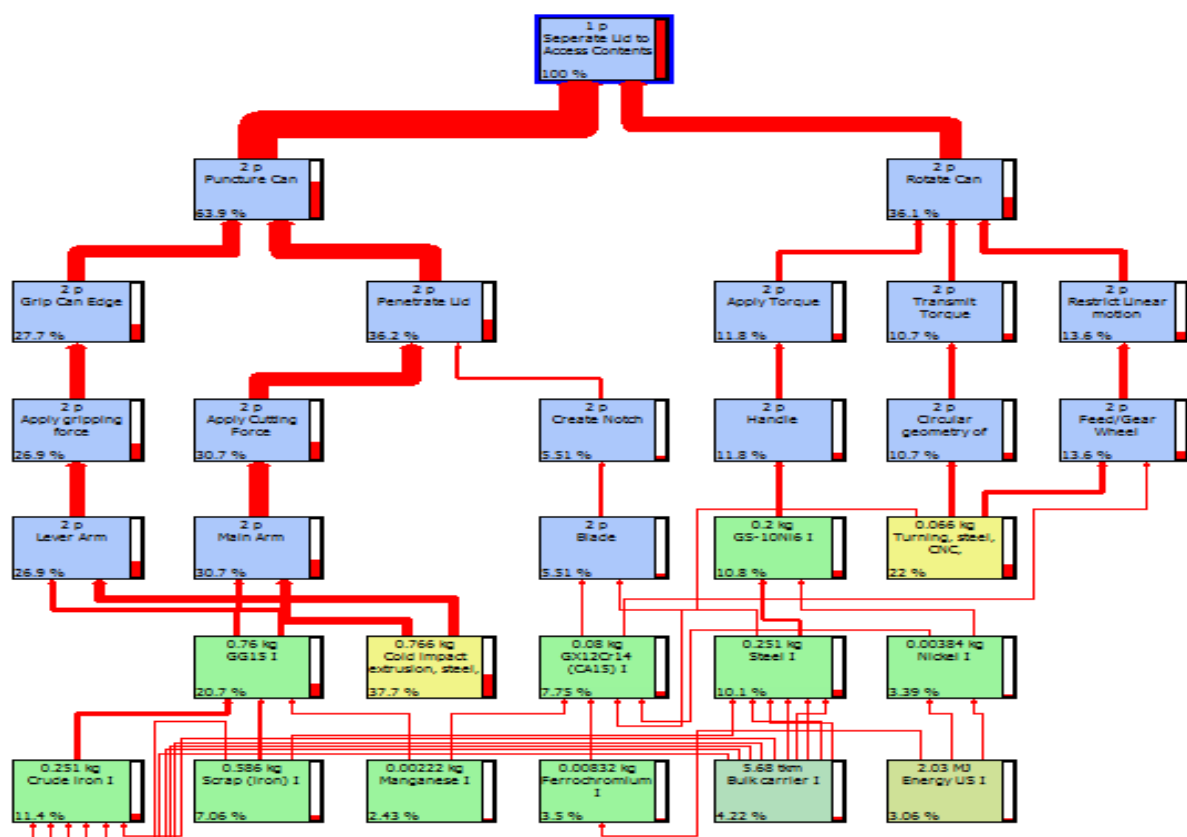


Figure 26: Environmental hotspot network for can opener

The drill down of the impacts throughout the hierarchy provides a structure for detailed investigation. In the Figure 27 is it clear that the puncture can module has higher impacts. With the drill-down of the structure it is observed that, inside the puncture can module, penetrate lid function has higher impact values.

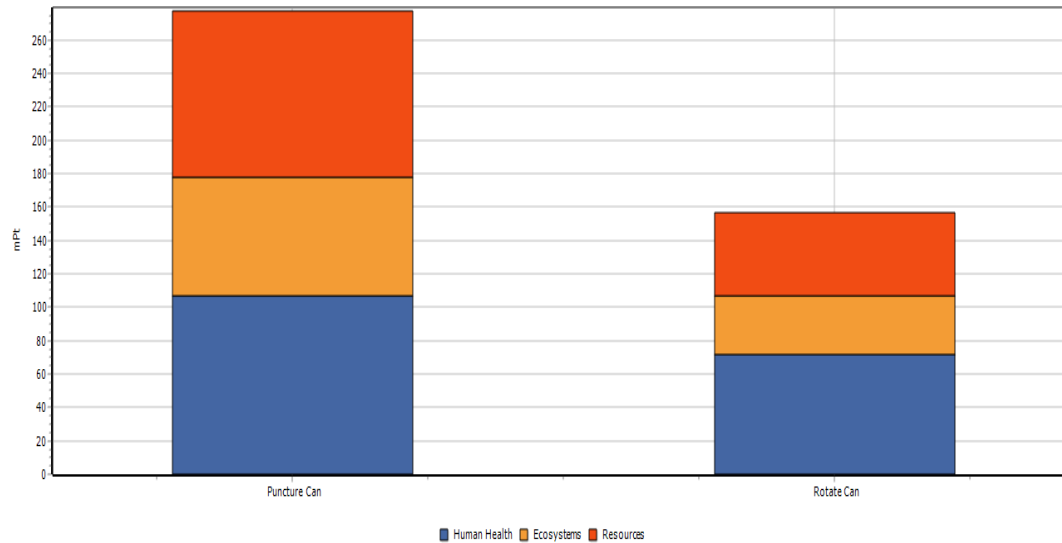


Figure 27: Environmental impacts of Puncture can & Rotate Can

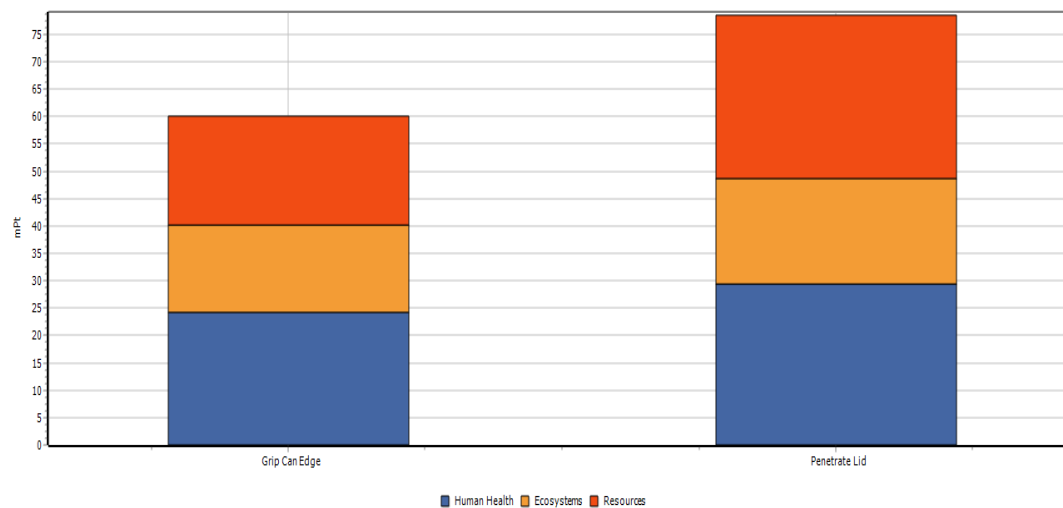


Figure 28: Environmental impacts of Grip can edge & Penetrate Lid

Apart from providing a hierarchical structure for investigation the parameters set earlier can be easily changed to evaluate different use scenarios. Different scenarios are constructed by simply changing the values of the use parameters. The system parameters and the CDF values are calculated as described earlier. Hence as the allocation is changed based on different user parameters, the impacts of new scenario can be compared to the old one. The new scenario is named S1. The new set of use parameter values is shown in Figure 29. Note that Parameters and the relationships are the same just the values have been changed to reflect changes in user behavior.

NumberOfCans_S1	150000	Undefined				<input type="checkbox"/>	
DiameterOfCan_S1	140	Undefined				<input type="checkbox"/>	mm
ThicknessOfCan_S1	1.2	Undefined				<input type="checkbox"/>	mm
Z_S1	2.2	Undefined				<input type="checkbox"/>	Material Property

Figure 29: Use parameter for Scenario S1

Currently the changes in the use parameter values automatically change the values of system parameters as the relationships are already established. The CDF values can be calculated and the allocation of modules performed automatically, if the limitations of SimaPro are overcome in the future software platform. The Figure 30 shows the CDF values and system parameters of the puncture can module for the new usage scenario. The Figure 31 shows the impact comparison of the original scenario and the new usage scenario.

PunctureForce_S1	$50 * \text{ThicknessOfCan_S1} = 60$	N
PunctureDepth_S1	$\text{ThicknessOfCan_S1} = 1.2$	mm
PunctureCycles_S1	$\text{NumberOfCans_S1} = 1.5E5$	
Ncr_S1	$\text{PunctureForce_S1} * Z_S1 * \text{PunctureDepth_S1} / Vcr = 1.58E5$	Critical number of cycles before failure
CDF_PunctureCan_S1	$\text{PunctureCycles_S1} / Ncr_S1 = 0.947$	

Figure 30: System parameter and CDF for scenario S1

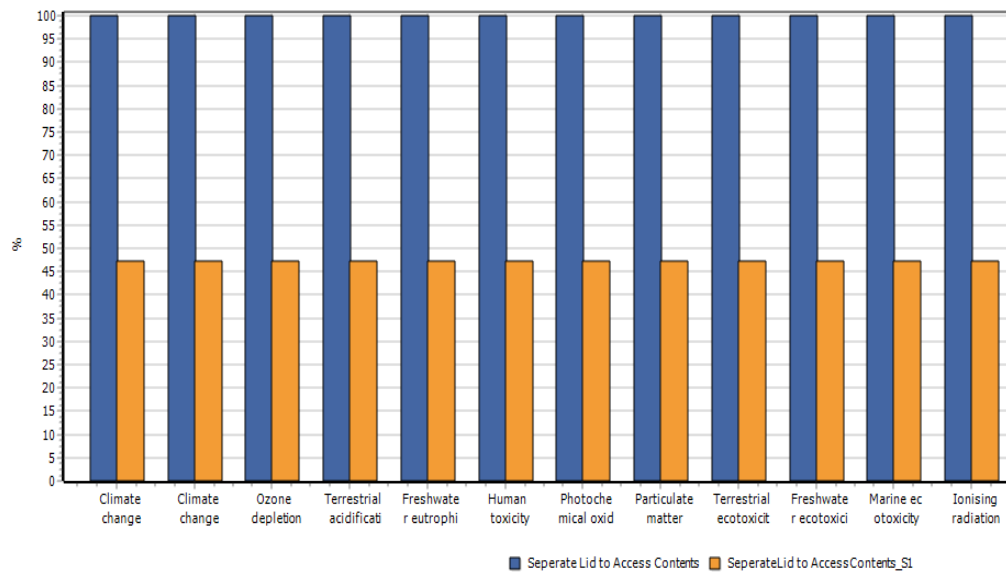


Figure 31: Comparison of environmental impacts between two use scenarios

The methodology explained above is implemented on a complex electro mechanical system to understand the challenges and areas for improvement. Next section explains the case study implementation on a Keurig 2.0 coffee machine.

5.0 Case Study Implementation

In this section, the methodology defined above is implemented on a more complex electro-mechanical system. The system was selected after many brainstorming sessions where the resulting alternatives included a Keurig coffee machine, an electric stapler, an electric vacuum machine, a desktop printer and a hand dryer. The criteria for selecting among the different alternatives are summarized in Table 2 . After a detailed comparison of alternatives, the Keurig coffee maker was selected, mainly because it had the desired number of functionally distinct electromechanical parts and use parameters. Also, the Keurig machine was manageable in terms of performing a teardown, generating a bill of materials and functional decomposition, considering the project timeline and resources.

Table 2: Product selection criteria

Criteria	Desired condition
Number of electromechanical parts present	Higher number of electromechanical parts is desired as it will help to cover a broad range of functions they satisfy. Along with it time and resource constraints are to be taken in consideration.
Presence of moving parts	More number of moving parts are desired as it will help to cover a broad range of stress parameters degrading the system.
Presence of interactions	System that actively interacts with human and requires human inputs is desired.
Generation of use cases	Presence of higher use parameters is desired as it will help to generate and analyze multiple use scenarios.
Number of technologies covering the main function	Presence of multiple technologies covering the same functions is desired to illustrate representation of a holistic system through functional decomposition.
Data availability	Ability to generate the Bill of material information through breakdown or other means is essential. Also, any possibilities for acquiring reliability data are to be considered.

5.1 The Keurig K 2.0 200 coffee brewing system-

Theory of operation

The Keurig coffee maker is used as a single serve coffee machine or to brew a carafe of up to 4 cups (6 oz./cup). The coffee grounds are contained in the K cup. The water required is stored in a reservoir which is part of the device. For brewing the coffee, the user opens the K cup holder and places the K cup in it. The user also selects the size of the coffee needed. When the start button is pressed the water from the reservoir is pumped to the electric heater that prepares the water for extraction. The air pump pressurizes and pushes the heated water into the extraction chamber. A piercing needle is used to pierce the K cup lid

and allow the passage of pressurized hot water into the K cup for extraction. The solute of the hot water and coffee extracts exits the system through a dispenser. The user thus gets a freshly brewed coffee that can be collected into a cup or carafe. For overview of the Keurig system refer to the Figure 32 and for the schematic refer to the Figure 33.

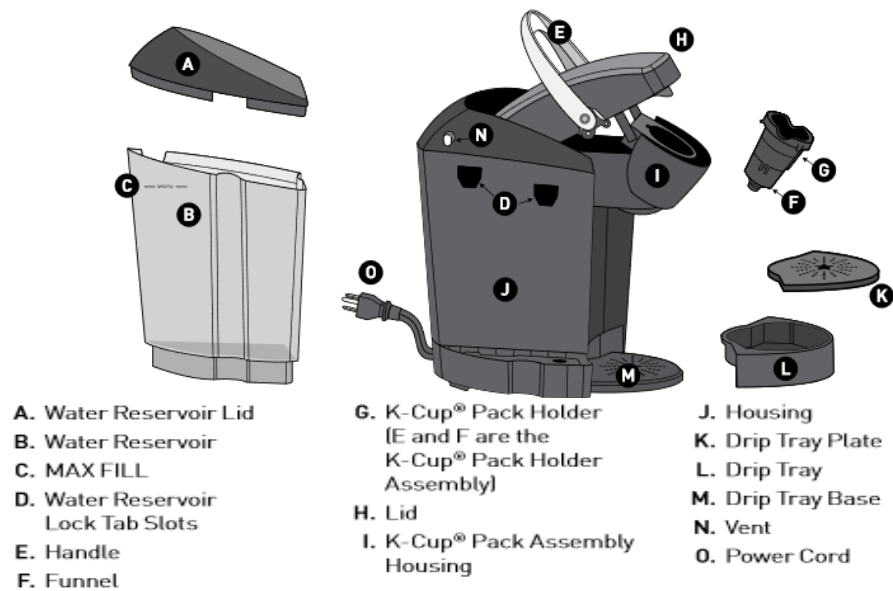


Figure 32: Keurig system overview (Keurig use & care guide K2.0 series, 2015)

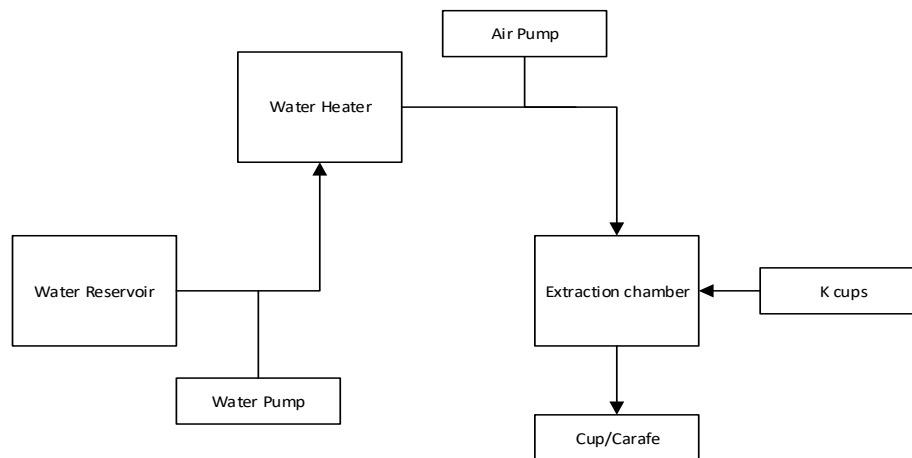


Figure 33: Keurig schematic layout

Coffee brewing

In order to adequately represent the system under consideration it was necessary to understand the coffee brewing process as a whole. Brewing coffee is a process in which water is passed through the coffee grounds to extract some chemical compounds (soluble) present in them. The mixture of water and dissolved chemical compounds is called as a solute. Once the desired concentration is obtained it is necessary to remove the coffee grounds from the solute. Additional flavoring like sugar and creamer is to be added according to the user needs. Every brewing technique adjusts a certain set of parameters so that the right chemical compounds are extracted.

The following parameters are adjusted to get the right blend (Thurston, Morris, and Steiman 2013)-

1] Grind particle size- The coffee beans are ground in order to increase the surface area that comes in contact with the water. The smaller the size of grinds the higher the rate of dissolution is. Grinds of different sizes extract at different rates; hence it is necessary to ensure the uniformity of particle size in order to obtain predictable brewing time.

2] Water Temperature- The water temperature directly affects the quantity of chemical compounds dissolved and the rate of dissolution. The rate of molecular activity increases with increase in temperature thus improving the opportunity for water molecules to come in contact with coffee grinds. Hence hot water is essential for efficient extraction.

3] Water Pressure- The water pressure has a similar effect as that of water temperature. With increase in the water pressure the molecules come in contact with the grinds more often. Thus, the higher the pressure the better the extraction efficiency is.

4] Agitation- The agitation has the same effect as the water pressure and temperature. Various methods can be used for agitating the mixture. In a filter brewing system it occurs as the water leaves the filter through the pores due to gravity.

5] Water to coffee ratio- The brew strength is measured in terms of total dissolved solids (TDS). TDS is defined as the percentage of coffee solids dissolved in water. The Specialty Coffee Association of America (SCAA) recommends the coffee strength to be between 1.0-1.5 percent TDS. This can be achieved by a coffee to water ratio of 1:18 by weight.

6] Contact time- The longer the water is in contact with the coffee grinds the higher the amount of extraction is. The ideal contact time cannot be set independently as it is largely dependent on the other parameters discussed above.

7] Filter type- The filter type has an effect on the extraction time as well as the type of chemical compounds that are part of the final brew. The smaller the holes on the filter the slower the rate of brewing is which in turn increases the extraction yield. Different types of filters trap different chemical compounds especially oils extracted from the beans.

8] Water quality- The coffee is almost 98.5% water and hence water quality dictates the quality of the final brew. Small changes in the mineral content, alkalinity and chemical additives can have a major impact on the coffee extraction. The mineral content of water directly affects the bonding capacity with coffee soluble which can suppress all the other extraction variables. The SCAA recommendation for water quality is “use water at or near neutral PH, containing 75-250 ppm dissolved solids and 20-85 mg/liter calcium hardness with little or no other elements or compounds like chlorine, Sulphur or silicates” (Speciality Coffee Assosiation of America, 2016).

5.2 Implementation of Methodology on Keurig System

5.2.1 STEP 1: Functional decomposition and identification of reference flows

The main function is independent of any technology used to brew the coffee. The function is generalized to the extent where it applies to a very wide range of possible technologies to implement the function.

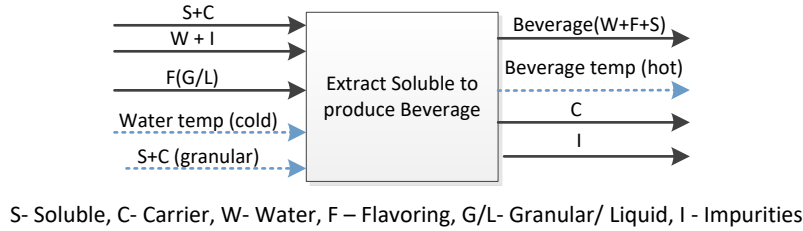


Figure 34: Main function of a coffee machine

From the Figure 34 it can be seen that the inputs required to make a cup of coffee are W- Water, S-soluble (chemical compounds to be extracted from coffee grinds), C-carrier for soluble (everything in the coffee grinds except the soluble) and F-flavoring (sugar, creamer etc.). It is assumed that the input water comes with Impurities-I, that need to be separated. During the process the soluble is extracted from the carrier to produce a mixture of hot water and soluble, finally flavoring is added (W+F+S). The Carrier-C and Impurities-I are separated and disposed.

The states of the inputs and outputs for the process are also taken into consideration. Different state assumptions can lead to different solutions. The desired state of the beverage is hot; accordingly, the state of output beverage is indicated clearly. Similarly, the states of the inputs like water, flavoring (granular / liquid) and Solution and carrier (granular) are identified. The coffee brewing is represented in the form of transformation of inputs into outputs as a ‘verb-noun pair-inputs’ to ‘verb noun pair-outputs’. Hence the main function for brewing coffee is presented as ‘Extract Soluble to produce Beverage’.

This same abstraction and method of representation is applied throughout the top down hierarchical decomposition process. The main function is further decomposed into four sub functions namely extract soluble, dispense beverage, mix flavoring (with water and soluble mixture) and communicate with user as shown in Figure 35. The Keurig machine does not support the mixing of flavoring with the mixture of water and soluble, this is performed by the user. Hence this function is left out of the further analysis. However, as a generalized representation is being developed, it is important to

model and decompose the functions in a manner where, the decomposition included the full set of functions required to complete the entire function for the user even if the system is not performing the function (in this example, to some users the coffee is not coffee without their cream and sugar). Note that this complete representation helps to ensure that any technology of brewing coffee that integrates the mix flavoring functionality can be mapped to the class representation if needed.

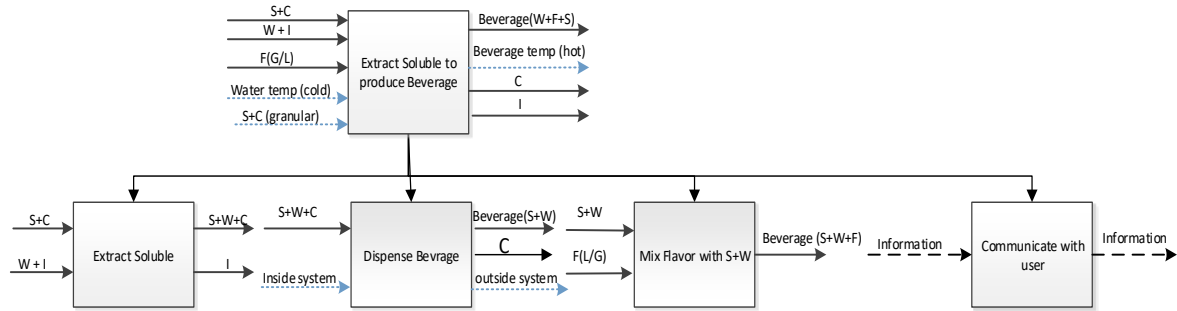


Figure 35: Decomposition of main function of coffee maker into Level 1 sub functions

Next, the further decomposition of each of these four sub functions into the second, third and subsequent levels is explained.

1] Extract soluble-

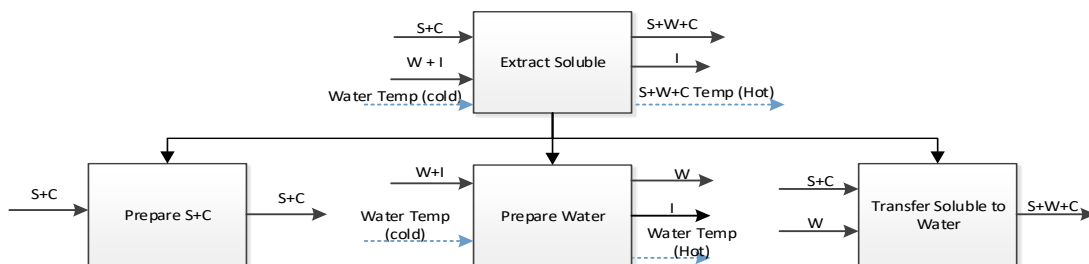


Figure 36: Decomposition of Extract soluble into Level 2 sub functions

The extraction of the soluble is the core process for brewing. The inputs required for this process are the coffee grounds and the water. It is assumed that the water contains impurities that need to be separated.

The process transforms these inputs into the mixture of soluble, hot water and the remaining carrier

compounds. For efficient extraction, the inputs need to be properly conditioned, hence the prepare water and prepare S+C are two important sub functions. Actual extraction takes place by transfer of the soluble to the hot water. Note that these three sub functions are the second level sub functions. Their further decomposition into the third level of decomposition is explained below.

The preparing of water includes accepting and containing the water in the system, separating the impurities from water to maintain the right quality, regulating and transporting the water to the heating system and heating the water to the desired temperature, refer to the Figure 37.

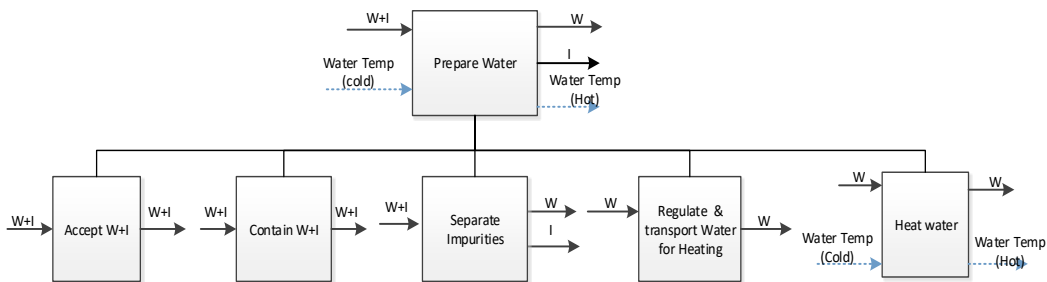


Figure 37: Decomposition of Prepare Water into Level three sub functions

Similarly, the conditioning of coffee grounds includes accepting and containing the grounds in the system as shown in the Figure 38. It is assumed that the input to the system is in the form of coffee grounds and not beans. If the input is in the form of coffee beans, then grinding is required i.e. the function increase the surface area for efficient extraction and it can be part of the system. For current implementation, this function is performed outside of the system boundaries. This function is not decomposed any further. For any other technologies that implements this function internally it can be integrated as an independent module. The important point is the structure is in place for its inclusion.

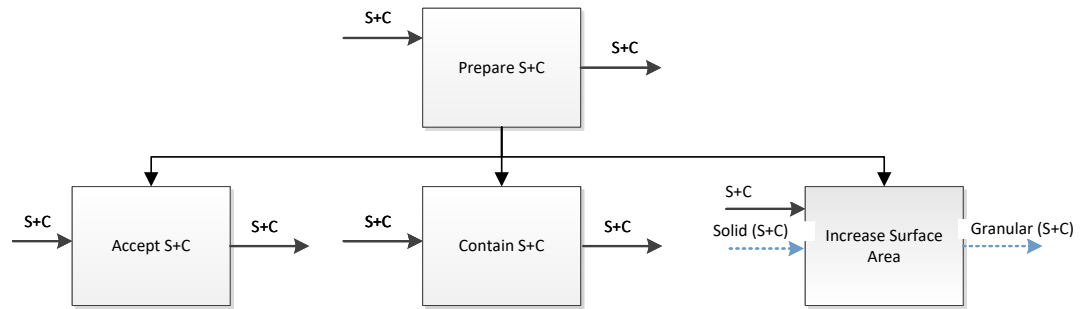


Figure 38: Decomposition of Prepare S+C into Level three sub functions

Once all of the inputs are properly conditioned the soluble is transferred to the heated water. In order to make this transfer efficient heated water is pressurized. Contact is established between the hot pressurized water and the grinds for an appropriate time period, the chemical compounds from the coffee grinds dissolve into the water.

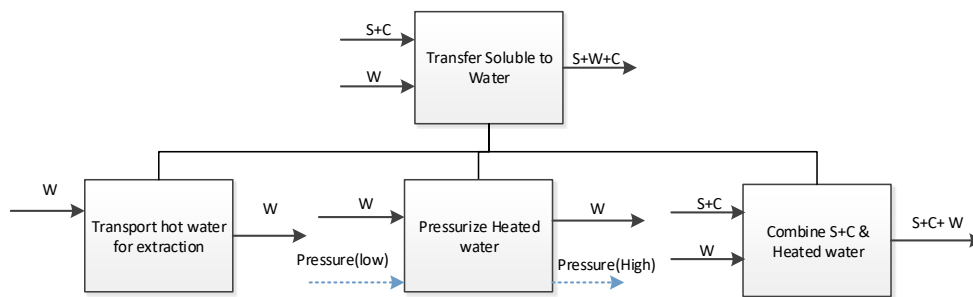


Figure 39: Decomposition of Transfer Soluble to water into Level 3 sub functions

2] Dispense beverage - Once the transfer of the soluble to the heated water is complete, the carrier is filtered out from the brew. The beverage then needs to be collected in some container. It is essential to properly position and secure the container. If the capacity of the collection media is less than the brew, there are spills. Provisions can be made to collect the drip and eventually dispose it off refer to the Figure

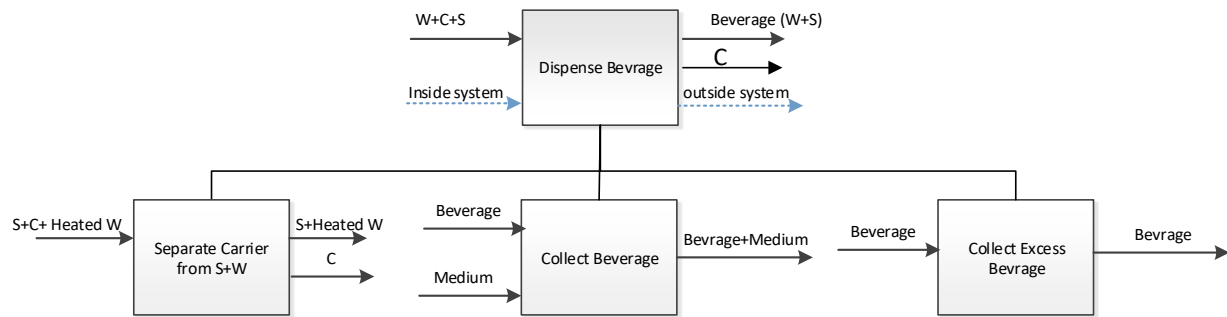


Figure 40: Decomposition of Dispense Beverage into Level 2 sub functions

3] Mix flavoring (with water and soluble mixture)-

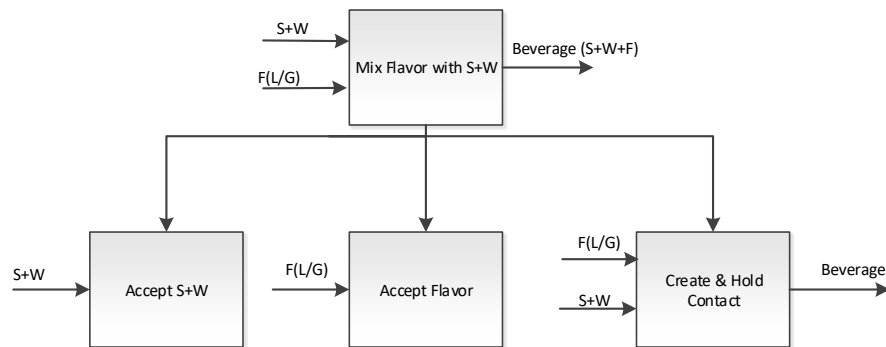


Figure 41: Decomposition of Mix flavor with S+W into Level 2 sub functions

People may add some additional flavoring like sugar and creamer to the brew. The flavoring type and quantity is accepted into the system based on user needs. The contact between the flavoring and brewed mixture has to be established. In the current implementation, this functional block is considered outside of the system boundaries, hence this function is not developed any further. The mix flavoring function can be thought of as an independent module which can be integrated in the future if necessary.

4] Communicate with user- An important part of an electro-mechanical system is the user interface. The user interface establishes a bidirectional transfer of information between the system and the user. The communication with user influences the system behavior and the implementation of logic. This communication Includes accepting the user inputs, interpreting the information user entered, displaying

information and sounding any alarms or alerts. Information flow is the only dominant flow for these functions. There are no material transformations taking place during implementation of these functions.

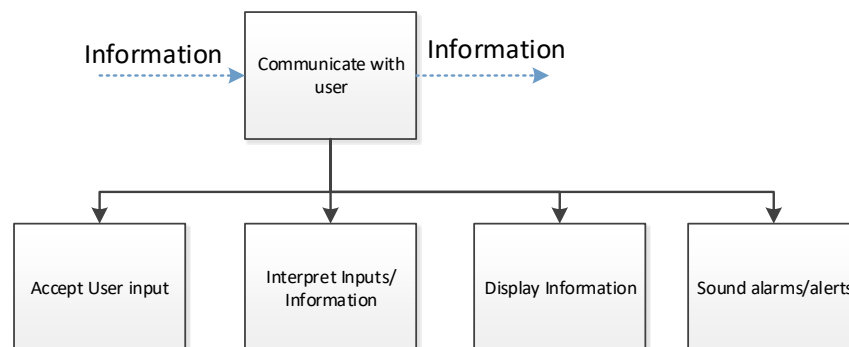


Figure 42: Decomposition of Communicate with user into Level 2 sub functions

The notion that the decomposition is form independent has been maintained in the previous discussions. As we progress down the hierarchy, the abstraction levels decrease, the levels of detail increase and more decisions are made about the particular technological solutions that implement the functions. Functional decomposition is an iterative process; assumptions are made from one level to the next. It is important to note that an important goal of this process is the controlled and slow convergence from solution independence to the specific solution elements of the system. For a detailed view of the complete functional decomposition refer to the Appendix B.

A useful technique to ensure completeness of the hierarchical function structure is to employ a bottom up approach. It will always be the case that if an LCA is to be executed a solution has to be defined. Thus, a reverse engineering method can be used that takes this into consideration. A detailed Bill of materials (BOM), which identifies all of the major and minor subassemblies, as well as the components, is generated from the defined solution. The basic, low-level functions of all the components should be noted in the BOM. It is also recommended that the features associated with these basic functions be identified. The detailed bill of materials (BOM) for the Keurig machine which was generated can be reviewed in

Appendix A. The bill of material was constructed by first identifying the major subassemblies of the product. The Keurig machine is a combination of following primary modules/subassemblies-

1] Water reservoir assembly and filter assembly-

The water reservoir assembly consists of a 40oz water tank with a lid. The water filter assembly rests in the water tank with the help on an attachment. The filter can be removed as necessary to replace the filtering element periodically. The spring and the plunger at the bottom of the tank regulate the flow of water from the tank to the heater. This assembly is shown in Figure 43.



Figure 43: Water reservoir assembly and filter assembly

2] K cup holder assembly-

The K cup holder mainly consists of the gripper that helps to secure the K cup in the system. It also holds the bottom piercing needle assembly. When the k cup is located in its position the needle pierces the bottom of the k cup to create a passage for the solute (water +soluble) to the dispenser guide. This ensures the exit of the brew from the system after the extraction is complete.



Figure 44: K cup holder assembly

3] Top jaw-

The top jaw holds the upper piercing needle frame and handle assembly. When the K cup is placed in its position and the system is closed, the upper piercing needle pierces the K cup lid. It is a hollow needle that allows the passage of hot water from the heater into the k cup where extraction takes place. It also holds the rotating pins and the handle assembly that facilitate the opening and closing of the system. Refer to the Figure 45.

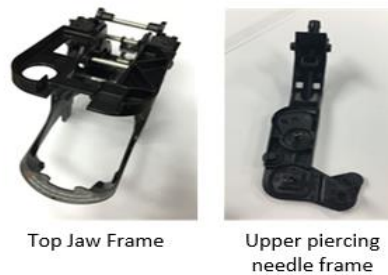


Figure 45: Top jaw and piercing needle frame

4] Bottom jaw-

The bottom jaw acts as a mounting for the entire k cup holder assembly and the dispenser guide.



Figure 46: Bottom Jaw

5] Air pack-

The air pack is used to pressurize the heated water and transport it to the k cup. It consists of an electric motor and the air pump. The compressed air from the air pump is forced onto the heated water with the help of a three-way valve assembly. All the tubing needed to accomplish this also included in the air pack. Note that the air pump and motor is an outsourced subassembly from a supplier.

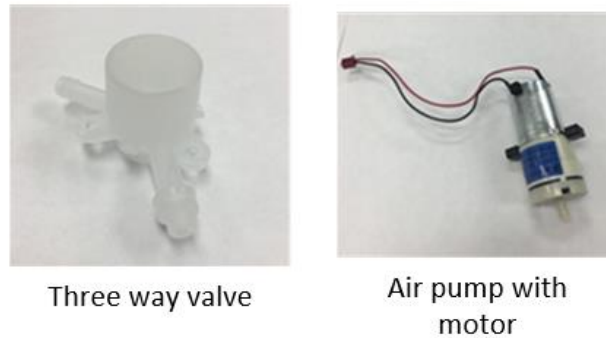


Figure 47: Air Pack

6] Water pack-

The water pack is used to transport water from the water reservoir to the water heater. It consists of a water pump that is drive by an electric motor. All the piping required is also a part of the water pack. Note that the water pump and the motor is an outsourced subassembly from a supplier.

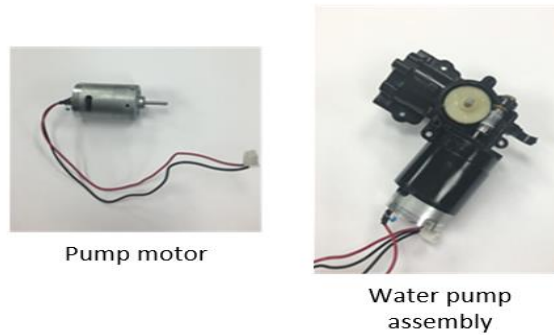


Figure 48: Water Pack

7] Electronic assembly-

The electronic assembly controls the logic of the machine. It helps to interpret the user inputs, monitor and regulate important parameters like temperature and pressure. The PCB is an integral part of the electronic module.

8] Base and enclosure-

The base of the machine acts as a mounting and support for all the sub-assemblies. The side and the front panels provide the enclosure to the system isolating it from the environment.

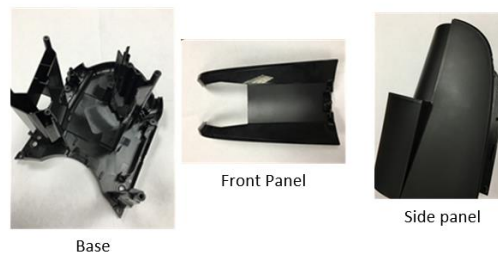


Figure 49: Base and Enclosure

9] Heater module-

The heater module consists of the heater coil, top cover and the bottom heater container, temperature sensors. Electricity is supplied to the heater coil which generates heat using resistive heating principle.

The heater coil is mounted inside the bottom heater container `which holds the water to be heated for

extraction. The top cover ensures that heat is retained in the enclosure and allows space for water expansion after heating. The temperature sensor is attached to the side of the bottom heater bowl to monitor the temperature and to provide feedback to the electronic circuit. Note that the Heater module is considered as an outsourced subassembly from a supplier.



Figure 50: Heater module

10] K cups- The K cups are considered as consumables required for every cycle. K cup is a conical plastic container with a paper filter used to store the coffee grinds. It also has a plastic lid on the top to enclose the grinds.



Figure 51: K cup (Keurig use & care manual k2.0 series, 2015)

For the detailed BOM for the Keurig machine refer to the Appendix A. The BOM consists of ten major assemblies, sixteen 2nd order assemblies, five 3rd order assemblies and 160 components. Note that some of the subassemblies are considered as outsourced, hence it is advised to work with the higher-level functions of these subassemblies.

In order to understand the basic functions of the Keurig machine parts, the operation of the machine with removal of these parts is mentally simulated. Once these basic functions are understood the question of which higher level functions are supported by these basic functions is addressed. Hence these basic functions are added to the top-down decomposition generated earlier and the respective components and features are mapped to the low-level functions.

It was observed that the majority of functions identified by the bottoms- up, ‘Subtract and Operate’ approach are functions that provide structural support for the system and include active verbs such as hold, constrain, join, support, mount, and grip. Furthermore, Energy is the dominant flow at this lower-level of detail, which makes sense since energy flows, in most of the cases, are dependent on the solution implemented to satisfy the function. This validation exercise ensured the comprehensiveness and the accuracy of the function structure developed. Two of the interesting observations that were made during this process are discussed further below-

1] Reversible functions –

A need to categorize certain functions as reversible functions was recognized during the process. A reversible function satisfies opposing functionality with the same set of sub functions, components and features. For example, the ‘Insert K cup’ and ‘Remove K cup’ functions serve the opposite purpose, but the sub functions, components and features that are required to satisfy both the functions are the same. Thus, these two functions are grouped into a single building block ‘Insert/Remove K cup’. As seen in the Figure 52 both the functions require enabling of the rotation, transmission of the hand force and providing of rotational degrees of freedom. Subsequently the components associated with those functions, like rotating pins, circlips and bottom jaw as well as features like pin holes, are common to both the functions ‘Insert/Remove K cup’. The material flows for both the functions are the same, in this case it is the same K cup that is inserted to brew the coffee and removed after the brewing process. The only difference is in

the final state of the material, after execution of the 'Insert K cup' function the K cup is inside the system while after 'remove K cup' it is outside of the system.

The functional block 'Insert/Remove K cup' satisfies two higher level functions, 'Accept S+C (Soluble& Carrier)' and 'Separate Carrier'. Every time the coffee brewing cycle is performed both of the higher-level functions are executed. Hence the impacts related to the functional block 'Insert/Remove K cup' are allocated 50% to the 'Accept S+C' and 50% to the 'Remove Carrier' functions. This ensures that the impacts of the components related to the reversible building blocks are allocated correctly to the multiple higher level functions satisfied.

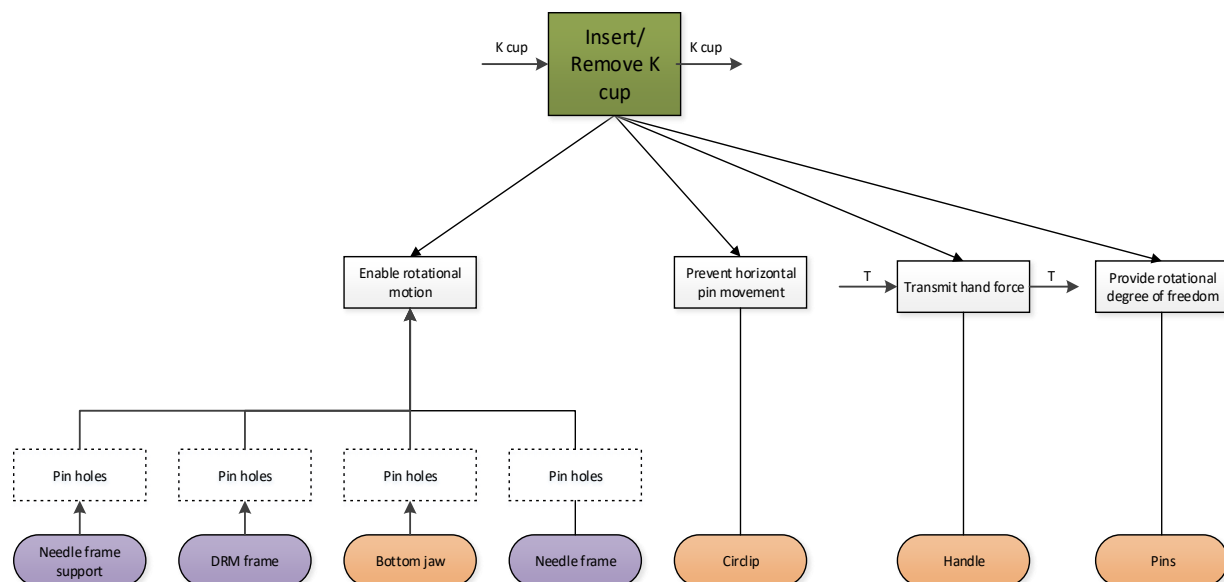


Figure 52: Reversible Function- Insert/Remove K cup

Some of the other examples of the reversible functions in our system are open tank lid/close tank lid, detach filter/attach filter, open the system/close the system.

2] The importance of component features-

In the process of mapping the components to the function structure tree, three possible scenarios were

identified. These scenarios have implications on the allocation of the environmental impacts allocation. These scenarios are discussed in greater detail below in a) – c] and illustrated in the respective figures.

a) Single component to Single function

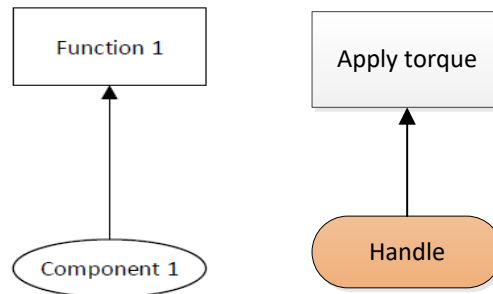


Figure 53: Single component to single function mapping

In this case, the component contributes 100% to the satisfaction of the function. The environmental impacts associated with all of the life cycle phases of this component can be attributed to 100% of the function. Hence this scenario does not present any challenges from an allocation perspective. For example, as seen in the Figure 54 , the only function that the handle satisfies is to apply torque and hence all of the impacts of the handle are linked to the apply torque function.

b) Single function to multiple components

In this case, one function is satisfied by a combination of multiple components, however each component contributes 100% to the function. Thus, the total impacts associated with the function is simply a summation of the impacts of all these contributing components. The scenario does not present any challenges from an allocation perspective. For example, for joining of the heater cover to the heater bowl functionality is satisfied by the nuts and screws. The environmental impact associated with the joining function is thus a summation of the impacts of all the life cycle phases of the screws and the nuts.

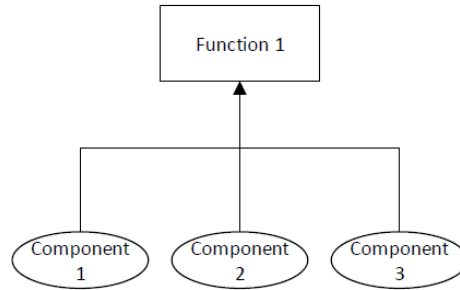


Figure 54: Single function to multiple component mapping

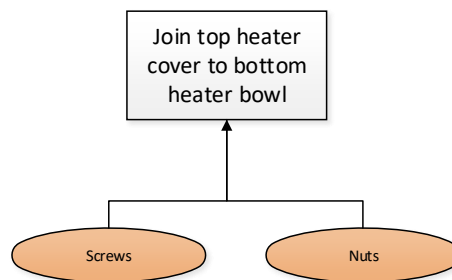


Figure 55: Join top heater cover to bottom heater bowl mapping

c] Single component to multiple functions

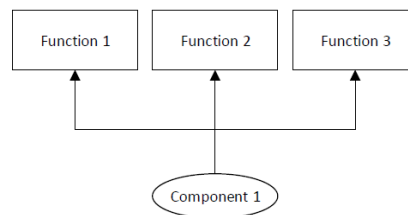


Figure 56: Single component to multiple function mapping

In this case, a single component is responsible for satisfying multiple functions. The levels of contribution from the component to satisfy these functions will be different which will affect how the environmental impacts are allocated. To address this issue, it was recognized that the components typically satisfy one main function while the remainder of the functions that are satisfied by component are done so through features that are added to the component. Furthermore, it was observed that the process steps that

generated these features were easily accounted for and could be used as the basis for allocating the environmental impacts. In some sense this is an activity based approach toward the allocation of the impacts. The representation of the inclusions of features is shown in the Figure 57. One can attribute the environmental impacts of component 1 across its lifecycle to the primary Function 1 and the environmental impacts of the generation of Feature 1 and Feature 2 can be attributed to Function 2 and Function 3 respectively.

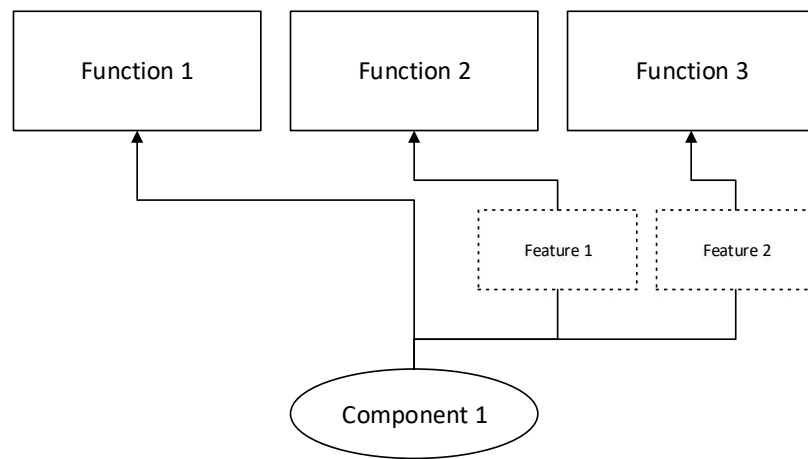


Figure 57: Function to feature and component mapping

In the Figure 58 the main function of the tank is to hold water, while the other functions are fulfilled by the features that have been added to the tank. Thus, the impacts across the life cycle of the tank are attributed with the ‘Hold water’ function while the impacts of the features are attributed to the respective supporting functions they fulfill.

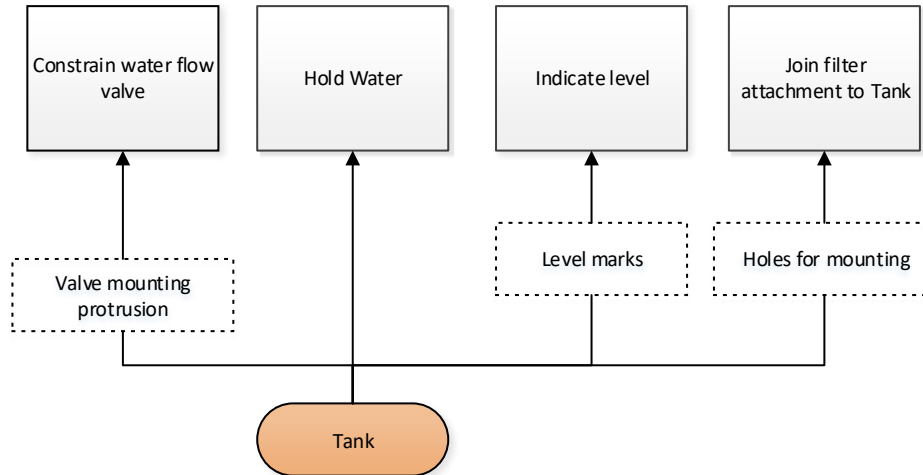


Figure 58: Mapping Tank & its features to functions

5.2.2 STEP 2: Establish Use parameters, System parameters and Cumulative Damage Function (CDF)

As mentioned in the previous section, the main function is represented in the form of a transformation of material inputs to outputs that is independent of the technology implemented. The reference flows that were identified for the main function act as a guide to define the use parameters of the system that implements this function and system parameters for the subsequent implementation of the sub-functions that support the main function. The use parameters are used to model the user behavior. The use parameters identified are not specific to any particular technology as they are derived from the reference flows. Changes in the consumer pattern can be modeled by changing the values and combinations of use parameters. The following section illustrates the implementation for the coffee brewing process.

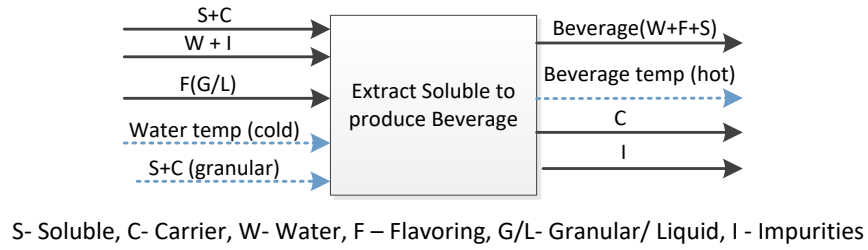


Figure 59: Coffee Brewing function

The Table 3 shows how the use parameters are derived from the input and output flows.

Table 3: Derivation of use parameters from reference flows

Reference Flow	Use parameter derived
S+C (Soluble + Carrier)	Quantity of Coffee grinds
S+C granular	Grind size of coffee beans
W+I (Water + Impurities)	Quantity of water
Water temp	Temperature of inlet water
F(G/L) Flavoring	Quantity of flavoring
Beverage(W+F+S)	Quantity of beverage, Quantity of beverage per serving
Beverage temp	Temperature of Beverage
C (carrier separated from the brew)	Strength of the coffee
I (Impurities separated)	Max TDS (Total dissolved solids in brew)

Some of the parameters will be eliminated based on system boundaries selected, but it is essential to list all the parameters while defining the main function. As an example, if the decision is made that the system will to not add the flavoring to the beverage, the use parameters and other derived parameters related to the reference flow F(G/L) become irrelevant to the analysis performed. Similarly, the grinding

of coffee beans is done outside of the system and hence the related use and derived parameters are not relevant

The Table 4 shows the use parameter values for the average usage scenario for a single day in America.

Table 4: Average daily usage scenario for coffee machine (See below for a detailed description and references for the parameters)

Use Parameter	Value
Quantity of Coffee grinds	1.47 oz
Quantity of water	26.44 oz
Temperature of inlet water	68°F
Quantity of beverage	27.9oz
Quantity of beverage per serving	9oz
Temperature of Beverage	140F
Strength of coffee	1.25%
Max TDS (Total dissolved solids in brew)	250ppm

1] Americans on average drink 3.1 cups of coffee per day and the average size of cup is 9 oz. Hence the ‘Quantity of beverage’ parameter is set to 27.9 oz. and ‘Quantity of beverage per serving’ is set to 9 oz (Coffee by the Numbers, 2010).

2] The National coffee association USA recommends a coffee to water ratio of 1:18. Hence to brew 27.9 oz. of coffee requires 26.44 oz. of water and 1.47 oz. of coffee grinds. The parameters ‘Quantity of water’ and ‘Quantity of Coffee grinds’ are set accordingly. (How to Brew Coffee , The NCA Guide, 2016)

3] The strength of coffee is the percentage of coffee solids (Soluble) dissolved in water. For ideal balanced coffee the strength is 1.25%, hence ‘strength of coffee’ is set to 1.25% (Speciality Coffee Assosiation of America, 2016).

4] It is assumed that the user feeds the inlet water at the room temperature on average 68°F (Speciality Coffee Association of America, 2016)

5] The Specialty Coffee Association of America (SCAA) recommends that for a good tasting coffee the maximum TDS (Total dissolved solids) should be 250ppm. Water quality is very important to coffee brewing as water constitutes almost 98.5% of total brew, hence impurities from water need to be controlled to maintain the TDS level (Speciality Coffee Association of America, 2016).

6] People tend to enjoy the coffee best when it is around 140F, hence the final beverage temperature parameter is set accordingly (The Ideal Temperature to Drink Coffee, 2016).

This parameter information can be deployed to the sub-functions through the functional hierarchy developed above. All of the required inputs at these lower levels are derived from the functions that they feed into. Consider the first level of the decomposition where the main function is broken down into four sub-functions. The system parameters for all these sub functions are derived from the use parameters defined earlier. The example of extract soluble sub-function is explained below, the other system parameters can be derived using a similar approach.

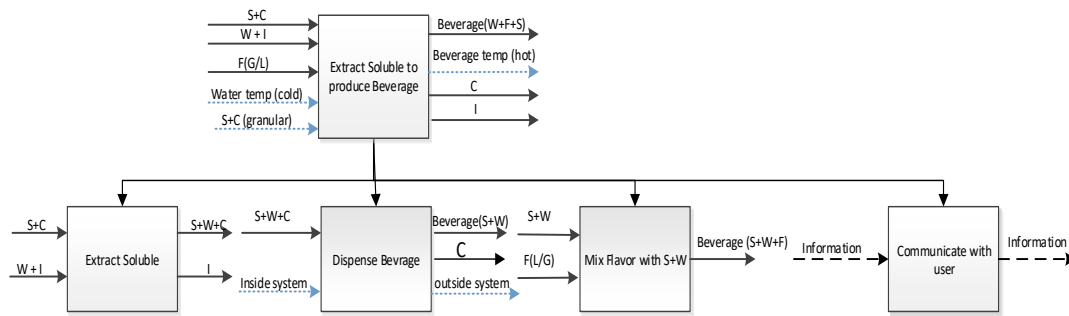


Figure 60: Decomposition of main function of coffee maker into Level 1 sub functions

Extract soluble-

a] Extraction yield/Extraction quantity- The extraction yield is the percentage of original dry coffee in the final brew. Extraction quantity is the quantity of soluble in the final brew.

$$\text{Extraction yield} = \frac{\text{mass of soluble}}{\text{quantity of coffee grinds}} = \text{Strength of coffee} \times \frac{(\text{quantity of water} + \text{quantity of coffee grinds})}{\text{quantity of coffee grinds}} \quad (9)$$

$$\text{Extraction yield} = 0.0125 \times \frac{26.44 + 1.47}{1.47} = 23.7\% \quad (10)$$

$$\text{Extraction quantity} = 0.237 \times 1.47 = 0.338 \text{ oz} \quad (11)$$

Hence all of the information required to derive the system parameters extraction yield and extraction quantity is available from the level above it (use parameters). Any changes to the user behavior will automatically be reflected in these system parameters through equations (9) – (11).

b) Extraction Temperature-

The extraction temperature is a direct function of the final temperature of the beverage desired by the user. Considering all the heat losses during brewing process the SCAA recommends an extraction temperature between 195- 205 F for a final beverage temperature of 140F. As a result, it is assumed that the extraction temperature should be 200F. This gives the clear relation as follows-

$$\frac{\text{Extraction Temperature}}{\text{Beverage temperature}} = \frac{200}{140} = 1.42 \quad (12)$$

Hence the extraction temperature is 1.42 times the beverage temperature. Thus, this system parameter can be derived from the use parameter ‘Temperature of beverage’.

d) Extraction Time-

The extraction time is largely dependent on the extraction temperature, strength of coffee and the quality of water. Extraction time is a complicated function of following use parameters-

$$\text{Extraction time} = f(\text{Temp of beverage}, \text{Strength of coffee}, \text{Max TDS in water}) \quad (13)$$

Once the use parameters are known the extraction time can be calculated. As a part of this work the actual relationship has not been derived due to the limited process knowledge. For implementation purpose, the extraction time of the Keurig machine was used directly.

e) Extraction clarity-

Extraction clarity can be directly derived from the use parameter Max TDS level desired in the final brew

$$\text{Extraction clarity} = \text{Max TDS} = 250\text{ppm} \quad (14)$$

f) Extraction cycles

Number of extraction cycles depend on the total quantity of beverage needed and the quantity of beverage that is made in each cycle.

$$Extraction\ Cycles = \frac{Quantity\ of\ beverage}{Quantity\ of\ beverage\ per\ serving} = \frac{27.9}{9} = 3.1 \quad (15)$$

The next step is to calculate the CDF's for each of the functional modules based on the current use scenario and function structure. The information that is summarized below is a summary of result from (Deo and Esterman 2016). For a detailed treatment of the development of the framework and its nuances, the reader is referred to (Deo and Esterman 2016).

The modules that have been identified are based on the separation of flows in the hierarchical decomposition and the knowledge of the Keurig system. As mentioned in the methodology ideally the modules should be identified independent of the solution using various clustering approaches. One such feasible approach is discussed in the future work section. The CDF values are calculated for a particular use scenario. Note the following:

- the average daily consumption scenario developed in the Table 4 is being used
- While only numerical values are shown in Figure 63 for the CDFs, similar to the system parameters described above, the CDFs are also parameterized and will adjust with changes in use scenarios (Deo, 2016)

Consider the example of 'Extract soluble' shown in Figure 61. The boundaries marked represent the independent modules identified in the Keurig system and their respective CDF values. One important flow is that of Soluble and Carrier (S+C) which should form a module. From Keurig, it is known that accepting S+C is satisfied by the top jaw subassembly and the containing of S+C is satisfied by K cup holder subassembly, hence these two form two separate modules. The next flow is that of water and impurities (W+I). The accepting and containing of water is made possible by the water reservoir assembly

hence these two functions form a single module. For the Separate impurities function the flow of impurities is separated from water hence this function can be considered as a separate module.

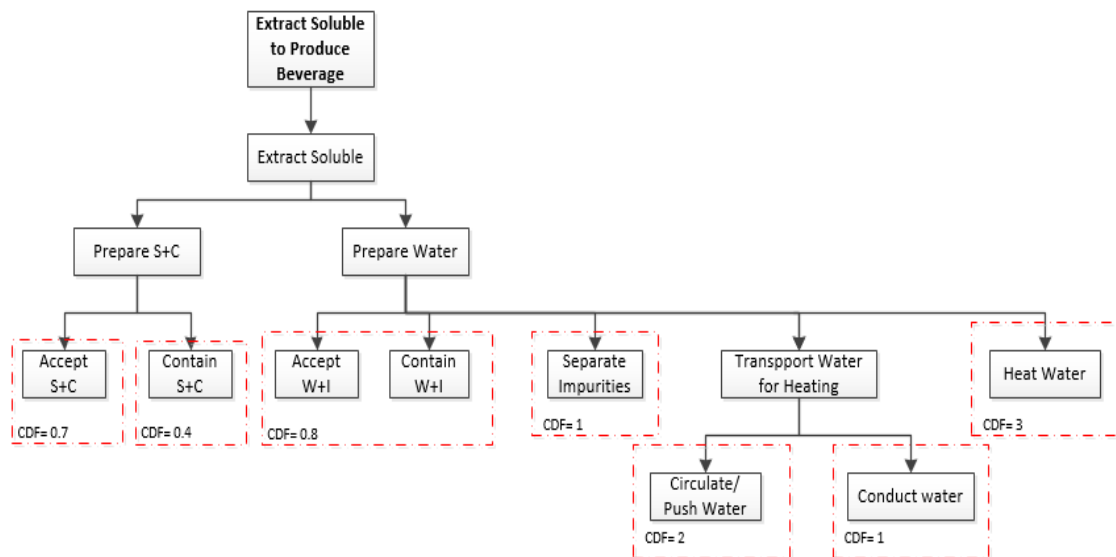


Figure 61:CDF allocation for Extract Soluble

Thus, once the use parameters are set and the hierarchical structure is defined, the information required to perform an LCA of each module independently, can be obtained. All the other solution specific parameters of the blocks which are at lower levels are hidden within the class.

An extremely important constraint that was necessary to ensure that was not being violated is that the information needed to define relationships within a function, needs to be available from functions that it feeds into or from functions that are at the same level of abstraction and detail as the function of interest. The reason for this is if information from lower-level functions is needed, the object-oriented portion has significant less value and less applicability during the design stages.

While verifying the above proposition, some interesting scenarios were uncovered that will be discussed below. For the system parameter of the water head for the water pump (module- Transport water for heating) one needs to know the location of the water tank and the heater. Note that the water tank is associated with the function 'Accept Water' and 'Contain Water' and the heater is associated with 'Heat Water'. Note both are part of the functional hierarchy at the same level of abstraction and detail. The

implication is that at this level of abstraction and detail, the architectural decision of relative position of these two functions will need to be. This is not problematic because this is constraints that comes with the design decision to select a pump as the solution to implement the function ‘Transport Water’ (which incidentally is at the same level of abstraction of detail). This information comes from position parameters which are part of two distinct classes. One approach to deal with this issue is to develop a set of interfacing parameters for classes through which the information can be shared. Developing interface parameters is not in the scope of this work and can be explored in future work.

5.2.3 STEP 3: Implementation using SimaPro

SimaPro has been the world’s leading LCA software package for 25 years. (About SimaPro, 2016). In SimaPro the product stages are used to construct the product under analysis. The Product is typically defined as a combination of different assemblies. Every assembly is constructed with the help of components. Each component is defined in terms of its material, weight and manufacturing process. SimaPro is designed to construct physical structure of the product, but not the architecture at the functional level. In our case the functions act as building blocks to create a hierarchical definition of product, which further connects to the structure. In order to overcome this limitation, dummy function blocks are defined under product stages. These functional blocks are then connected with each other following the hierarchy of the functional decomposition developed earlier. An assembly named Function-Structure was created for the Keurig machine with help of the function diagram and the BOM, refer to the Figure 62.

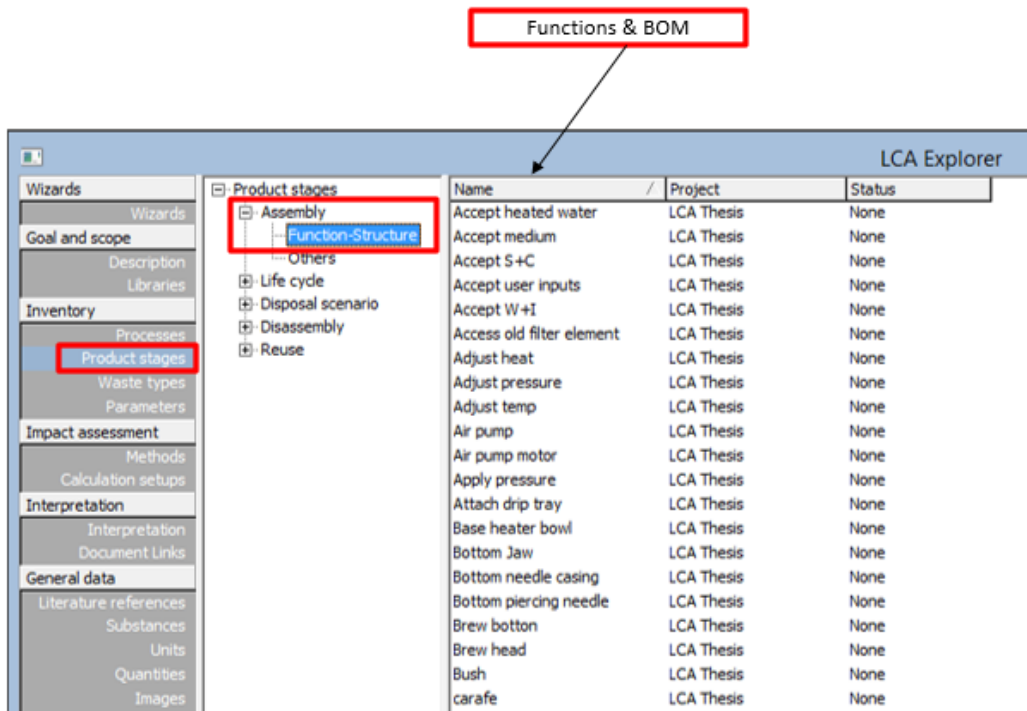


Figure 62: Function-Structure of Keurig in SimaPro

From the hierarchical decomposition shown in Figure 63, the main function Extract soluble to produce beverage is made up of four building blocks Extract soluble, dispense beverage, Communicate with user and Mix flavoring with S+W.

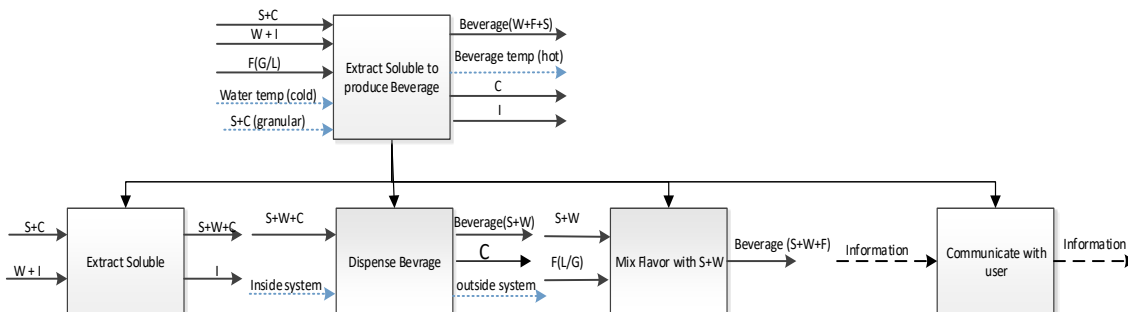


Figure 63: Decomposition of main function of coffee maker into Level 1 sub functions

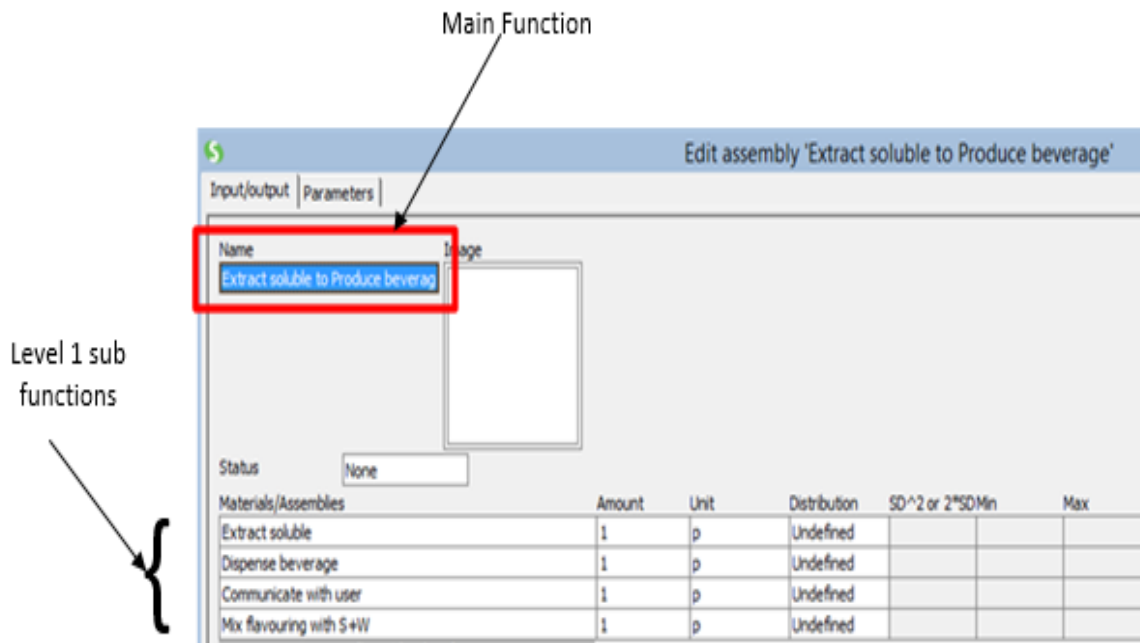


Figure 64: Main function to Level 1 function for Keurig

In SimaPro the Materials/Assemblies section is used to define the subassemblies or the materials that constitute the part/main assembly. In our case, lower level functions are the building blocks for the upper level functions, hence they are added to the section Materials/Assemblies to form the higher-level functions. Thus, Figure 64 implies that the 'Extract soluble to Produce beverage function' is a combination of Level one sub functions shown in Figure 63.

Consider the next level of decomposition in which the 'Extract soluble' sub function is further decomposed into three level two sub functions. It is represented in Figure 65. The same process is continued for all of the levels of decomposition.

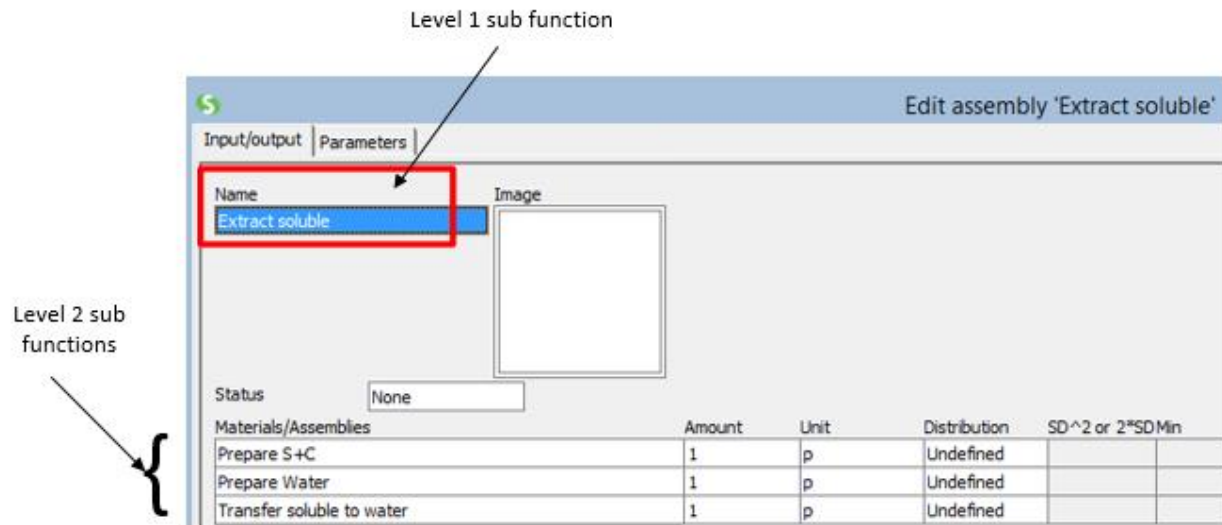


Figure 65: Level 1 to Level 2 mapping for Keurig

After performing the bottoms- up functional modeling the components and features are mapped to the lowest level functions in the decomposition. As an example, consider the lowest level function 'join top heater cover to bottom heater bowl'. This function is achieved by six screws and six nuts. It is also necessary to have the feature joining holes on the top heater cover to perform this function.

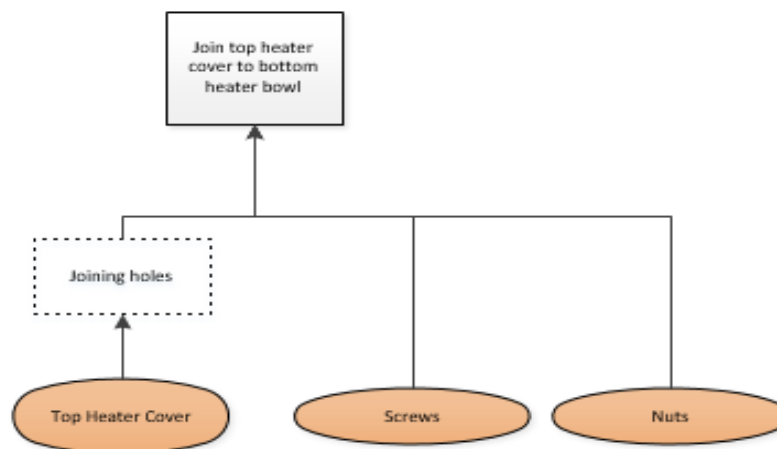


Figure 66: Lowest level function to structure mapping for Keurig

In SimaPro all of the components and features are expressed in terms of material and manufacturing processes. The details of materials and manufacturing processes used can be found in the Keurig BOM, Appendix A. An example of a component definition is shown in Figure 67 .

The screenshot shows the 'Definition of Nut' form in SimaPro. It includes a 'Name' field with 'Nuts', an 'Image' placeholder, a 'Status' dropdown set to 'None', and two tables for 'Materials/Assemblies' and 'Processes'.

Materials/Assemblies	Amount	Unit
Steel, low-alloyed, at plant/RER S	2	g
(Insert line here)		

Processes	Amount	Unit
Cold impact extrusion, steel, 1 stroke/RER S	3	g
(Insert line here)		

Figure 67: Definition of Nut in SimaPro

Finally, the lowest level functions are mapped to the components and features as shown in the Figure 68.

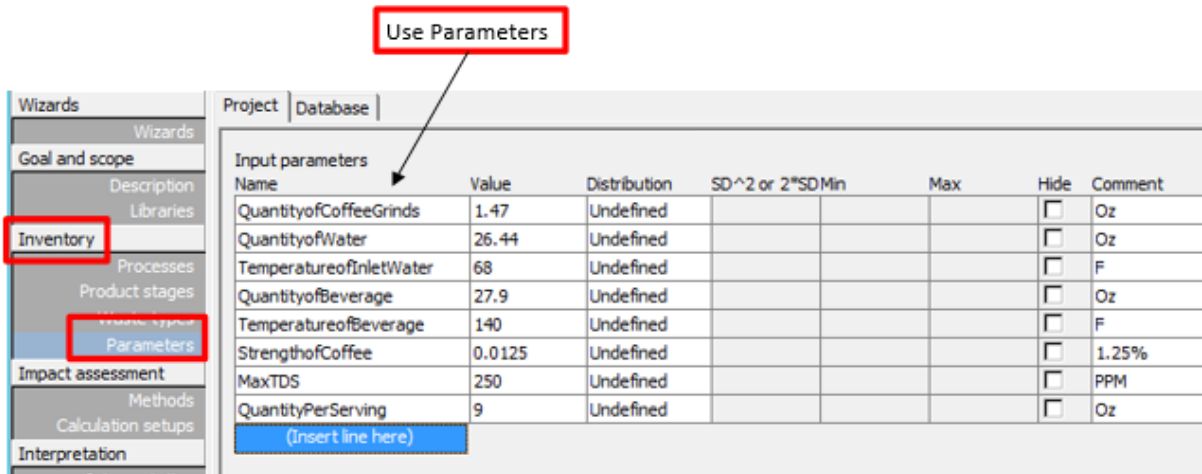
The screenshot shows the 'Lowest level function to structure mapping' form in SimaPro. It includes a 'Name' field with 'Join top heater cover to bottom he', an 'Image' placeholder, a 'Status' dropdown set to 'None', and a table for 'Materials/Assemblies'.

Materials/Assemblies	Amount	Unit
Screws	6	p
Nuts	6	p
Holes for joining	6	p

Figure 68: Lowest level function to structure mapping in SimaPro

After performing all of the above steps, a hierarchical network of functions connected to the physical structure is generated.

Below the setting up of the use parameters, system parameters and the CDF calculations will be explained. The use parameters which are derived from the reference flows of the main function act as the global parameters. These are defined in the parameters section under the inventory as shown in Figure 69. The values of the use parameters are entered based on the use scenario. By changing these values different use scenarios can be constructed easily. These use parameters are accessible to any part of the system.



Project Database							
Input parameters							
Name	Value	Distribution	SD ² or 2*SD Min	Max	Hide	Comment	
Quantity of Coffee Grinds	1.47	Undefined			<input type="checkbox"/>	Oz	
Quantity of Water	26.44	Undefined			<input type="checkbox"/>	Oz	
Temperature of Inlet Water	68	Undefined			<input type="checkbox"/>	F	
Quantity of Beverage	27.9	Undefined			<input type="checkbox"/>	Oz	
Temperature of Beverage	140	Undefined			<input type="checkbox"/>	F	
Strength of Coffee	0.0125	Undefined			<input type="checkbox"/>	1.25%	
Max TDS	250	Undefined			<input type="checkbox"/>	PPM	
Quantity Per Serving	9	Undefined			<input type="checkbox"/>	Oz	
(Insert line here)							

Figure 69: Use parameters of Keurig in SimaPro

Next, the system parameters for sub functions are derived based on use parameters. The connection between the use and system parameters of first level sub function 'Extract soluble' is established in SimaPro as shown in Figure 70. The derivation of these equations has already been discussed in a previous section.

Input/output		Parameters				
Input parameters						
Name	Value	Distribution	SD ² or 2*SD Min	Max	Hide	Comment
(Insert line here)						
Calculated parameters						
Name	Expression					Comment
ExtractionYield	QuantityofBeverage*StrengthofCoffee*100/QuantityofCoffeeGrinds = 23.7					percentage
ExtractionTemperature	1.42*TemperatureofBeverage = 199					F
ExtractionClarity	1*MaxTDS = 250					PPM
ExtractionTime	60 = 60					f(Temp of beverage,Strength of coffee,Max TDS in water)
ExtractionCycles	QuantityofBeverage/ QuantityPerServing = 3.1					

Figure 70: System parameters for Extract soluble

These parameters derived from user behavior are further related to the system parameters for the modules. The CDF expressions are then developed for each module in terms of use and system parameters. As mentioned above, the details of the methodology for the calculation of the CDF can be found in (Deo and Esterman 2016).

As a next step, the modules are allocated to their respective higher level functions based on the CDF values calculated. Consider the example of ‘Extract Soluble’ function shown in the Figure 71.

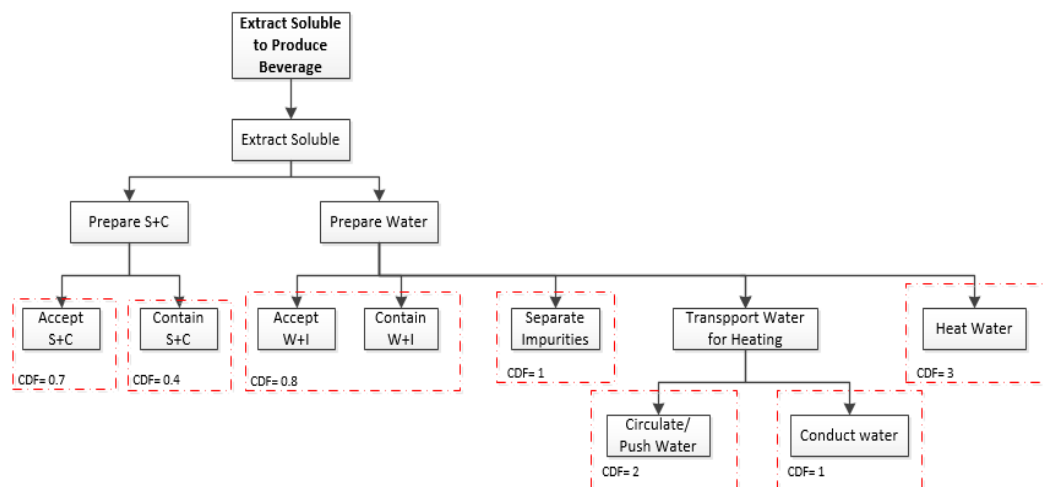


Figure 71:CDF allocation for Extract Soluble

The extract soluble function is made up of two lower level functions prepare S+C and prepare water, one unit of each of these sub-functions is allocated to the extract soluble function. Inside prepare S+C and

prepare water functions, the modules are formed and they are allocated based on their respective CDF values. According to the CDF values, point eight units of accept & contain W+I, one unit of separate impurities, one unit of transport water for heating and three heat water units are allocated to the prepare water function. Note that for the functions 'transport water for heating' modules are formed and CDF is calculated at a lower level. Based on the CDF values, two units of circulate/push water and one unit of conduct water is allocated to the transport water for heating function. The Simapro implementation is shown in Figure 72 and Figure 73. The automatic allocation of modules based on CDF values was not possible due limitations of SimaPro. These limitations for CDF calculation and allocation have already been discussed in the methodology section.


Input/output		Parameters					
Name	Image	Comment					
Prepare Water							
Status	None						
Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment	
Accept W+I	0.8	p	Undefined			CDF_Accept & Contain Water module	
Conatin W+I	0.8	p	Undefined			CDF_Accept & Contain Water module	
Seperate impurities	1	p	Undefined			CDF_Seperate impurities module	
Regulate water for heating	1	p	Undefined			Go to next Level	
Transport water for heating	1	p	Undefined			Go to next Level	
Heat water	3	p	Undefined			CDF_Heat Water	

Figure 72:Allocation for Prepare water function


Input/output		Parameters					
Name	Image	Comment					
Transport water for heating							
Status	None						
Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment	
Circulate/Push/Displace Water	2	p	Undefined			CDF_Circulate water module	
Conduct Water	1	p	Undefined			CDF_Conduct water module	

Figure 73: Allocation 'Transport water for heating'

Developing a Life Cycle

One of the main advantages of LCA is the ability to perform a ‘cradle to grave’ impact assessment. The lifecycle processes for transportation, energy consumption and disposal phases are described below. The life cycle of the Keurig machine is defined inside the product stages, shown in the Figure 74 . The details of the implementation are provided below.

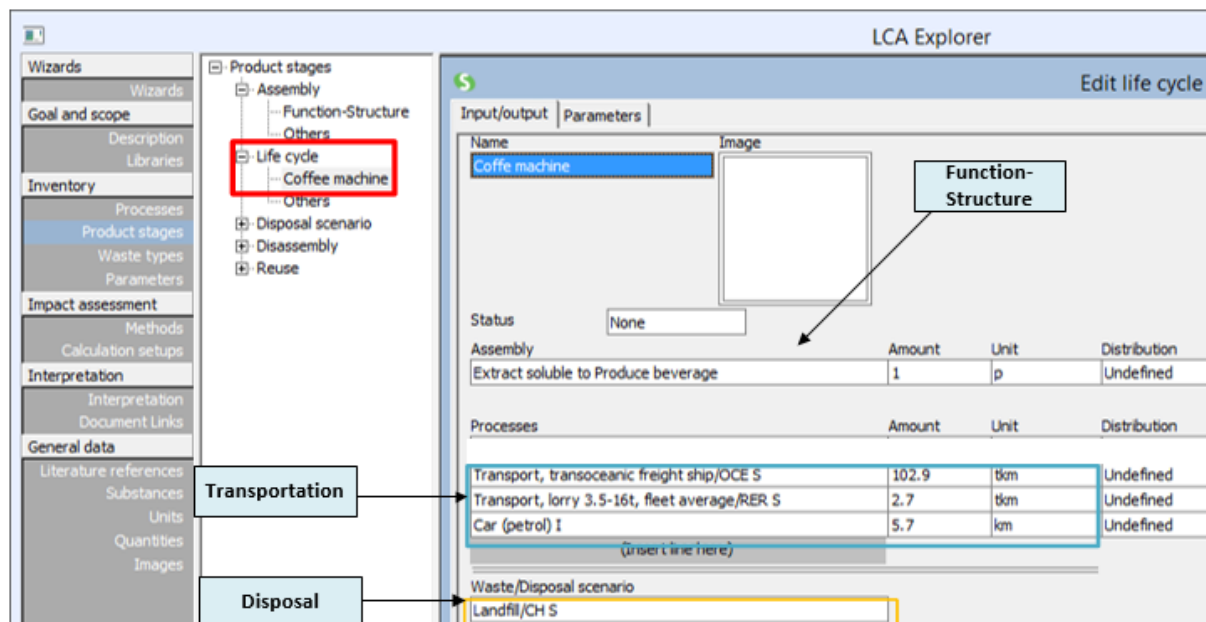


Figure 74: Life cycle of coffee machine

1] Transportation-

Keurig has outsourced the manufacturing operations to Simatelex, whose location is in Shenzhen, China. (Where Are Keurig Coffee Machines Manufactured?, 2016). It is assumed that the Keurig machine is shipped from Shenzhen to the Port of New York/New Jersey. The distance for this Transoceanic freight is 20588.12 Km as shown in Figure 75 (SeaRates.com, 2016). The weight of the Keurig machine is 5 Kgs. Hence the transoceanic freight distance in ton km is 102.9. The machine is then transported from the port of New York to Walmart (Rochester) by truck. The distance covered by truck is 331 miles (Distance

in ton km= 2.7). The machine is taken from the Walmart to the Rochester Institute of Technology by car and the distance is 3.6 miles. Note that the transportation of the outsourced systems from the supplier to the Keurig manufacturing plant is not a part of the analysis. Modeling of the transportation scenario is only at the device level. The transportation scenario is defined inside the lifecycle of the coffee machine as shown in the Figure 76.

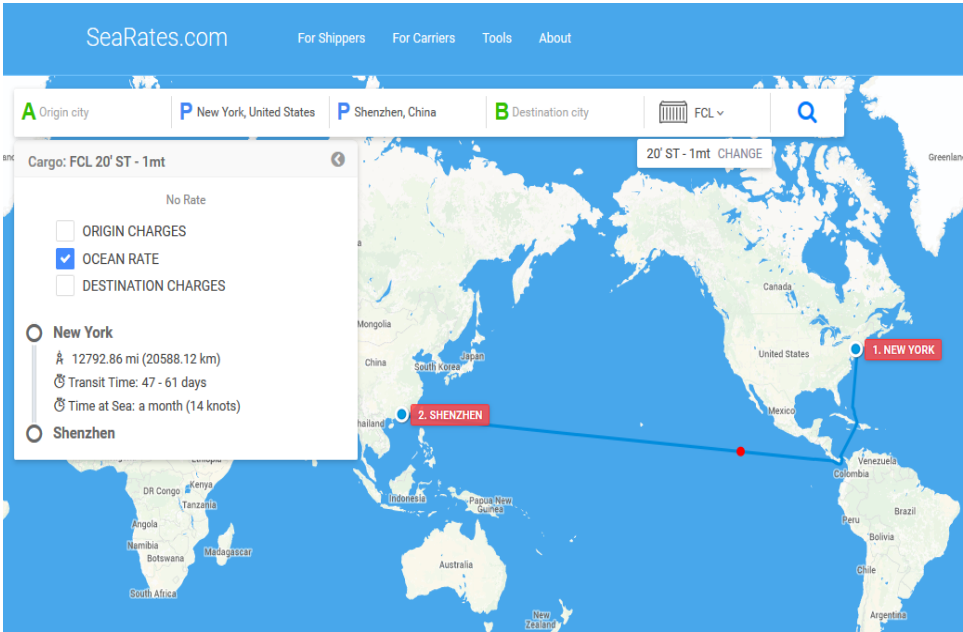


Figure 75: Sea route from Shenzhen to Port of New York

Input/output		Parameters			
Name	Coffe machine	Image			
Status	None				
Assembly	Extract soluble to Produce beverage	Amount	Unit	Distribution	SD^2 or 2*SDMin
		1	p	Undefined	
Processes		Amount	Unit	Distribution	SD^2 or 2*SDMin
	Transport, transoceanic freight ship/OCE S	102.9	tkm	Undefined	
	Transport, lorry 3.5-16t, fleet average/RER S	2.7	tkm	Undefined	
	Car (petrol) I	5.7	km	Undefined	

Figure 76: Transportation Scenario

2] Energy consumption-

The energy consumed is related to the use scenario with the help of the use parameters established. Note that the energy consumption is specific to the technology employed. In the case of Keurig electricity is the source of energy to operate the water heater, water pump, air pump and the user interface. The energy consumption is a function of the usage and the technology used.

$$\text{Energy consumed} = \text{Energy consumed per serving} \times \text{Total number of servings} \quad (16)$$

$$\text{Energy consumed} = \text{Energy consumed per serving} \times \frac{\text{Quantity of beverage}}{\text{Quantity per serving}} \quad (17)$$

The Keurig machine consumes 1290 Watts of energy when it is started to warm up for about a minute and for the actual brewing process it again consumes 1290 Watts of energy and the brew time is approximately one minute. Hence the Keurig consumes 0.044 kWh of energy per serving (Power Consumption, 2016). For the average daily use scenario for yearlong usage the energy consumption is given by-

$$\text{Energy consumed} = 0.044 \times \frac{\text{Quantity of beverage}}{\text{Quantity per serving}} \times 365 = 0.044 \times \frac{27.9}{9} \times 365 = 50 \text{ kWh} \quad (18)$$

The energy consumed of the water heater is mapped to the heat water function, energy consumed by water pump is mapped to the circulate/push water function, energy consumption of air pump is mapped to the pressurize air function and energy consumed by the user interface is mapped to the communicate with user function. By operating the device, it was observed that significant fraction of the total operating time the device is heating the water and keeping it at temperature for the next extraction cycle. During the extraction cycle, most of the time is used to pump and pressurize water. Hence based on our engineering judgement, out of the total energy consumed 50% (25 KWh) is allocated to 'heat water' module, 20% (10 KWh) to 'Circulate/Push Water', (20%) 10KWh to 'Pressurize air' and 10% (5 KWh) to 'Communicate with user'. It should be noted that a detailed study could be made to established these relationships more accurately. Once these relationships are established the energy consumption for different use scenarios can be modeled by changing the values of use parameters. The example of the 'Heat Water' module is

shown in Figure 77. The total energy per serving is defined inside the input parameters section. The calculated parameter section is used to relate the energy consumption of the heater to the use parameters.

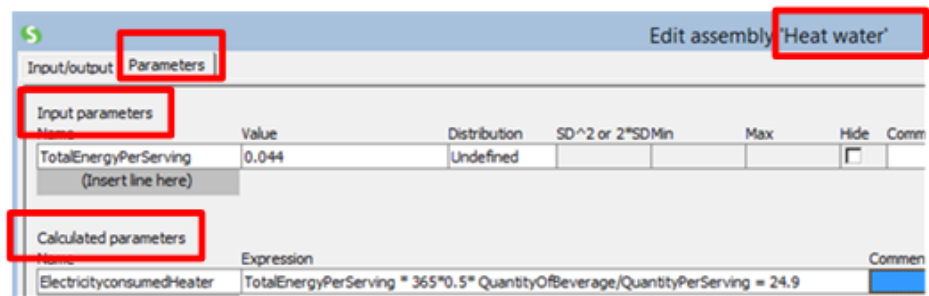


Figure 77: Energy calculation for Heat Water

In the processes section of the heat water module the energy consumption is allocated to the heater as shown in Figure 78.

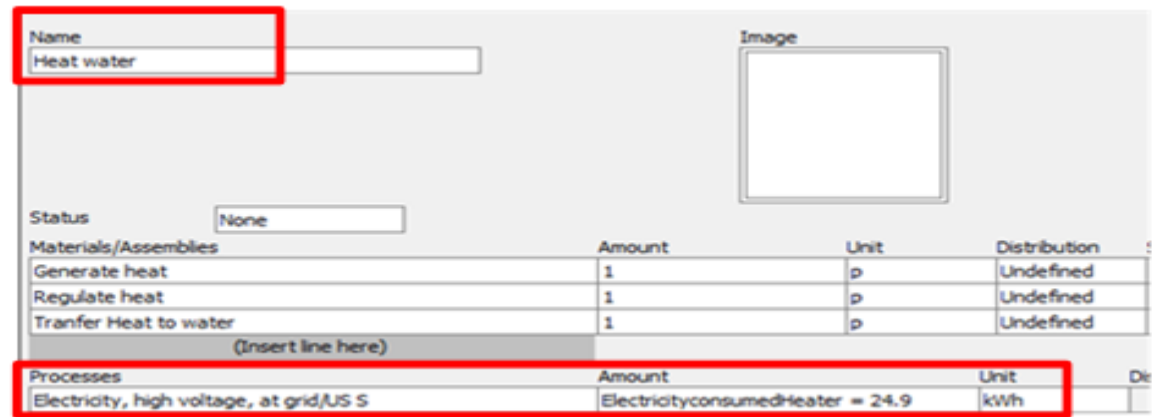


Figure 78: Energy Allocation for heater

It is assumed that everything goes to the landfill after the end of life of the product. The construction of different disposal strategies based on the user behavior and the function-structure is discussed in the future work section.

Finally, the impacts of the coffee machine for the use scenario are analyzed using end point impact assessment. The end point impact assessment calculates the impacts on human health, ecology and

resources. On a life cycle level, it is observed that the main process of Extraction of soluble has the highest impacts (refer to the Figure 79). The red bars in the figure indicate the environmental load generated by each block. Thickness of the red line and the red bars help to identify the environmental hotspots. The environmental impact values (Eco points) are shown in the Figure 80.

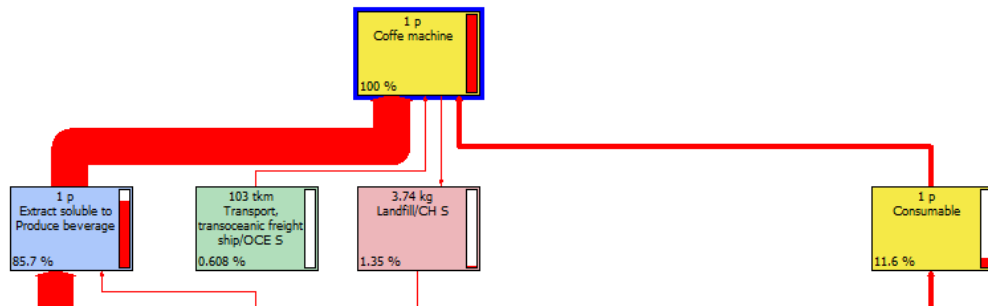


Figure 79: Lifecycle network of coffee machine

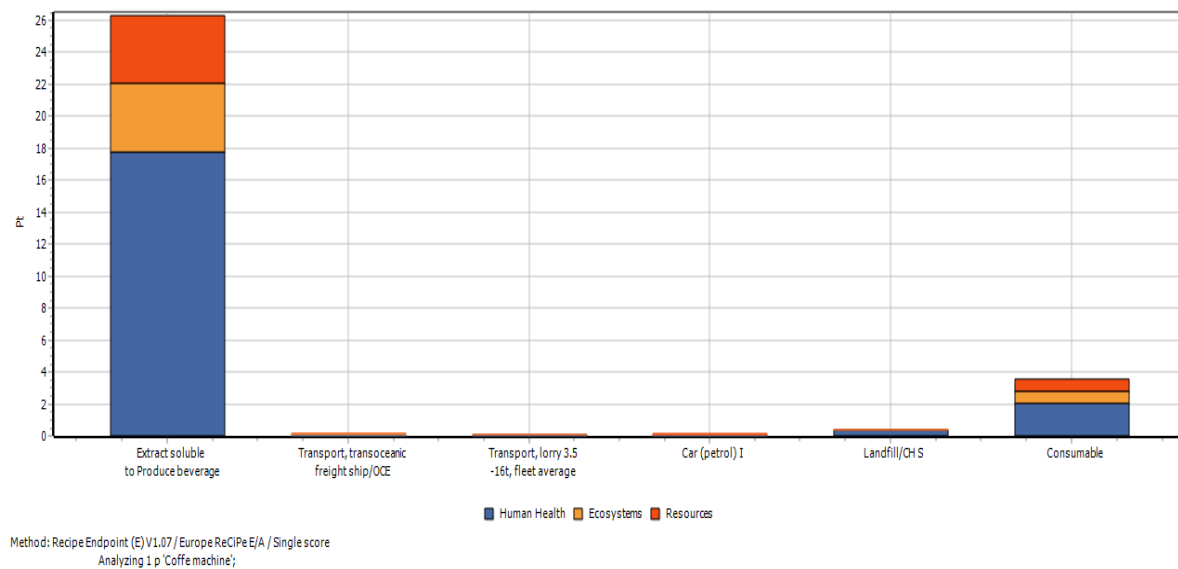


Figure 80: Life cycle impacts coffee machine

The analysis on a functional level indicates that the prepare water function is the environmental stress point (refer to the Figure 81). In the analysis of the lower level of the prepare water function, it is

observed that the heating of water and the transportation of the water for heating are major contributors to the environmental impacts.

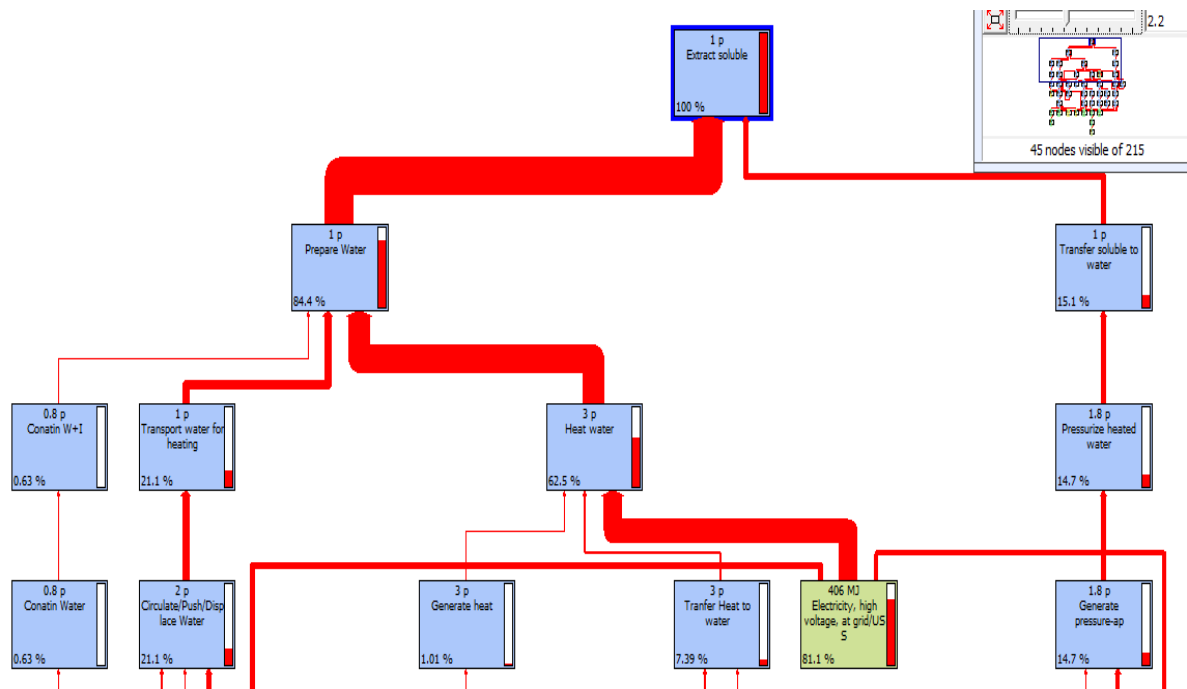


Figure 81: Impact network for extract soluble

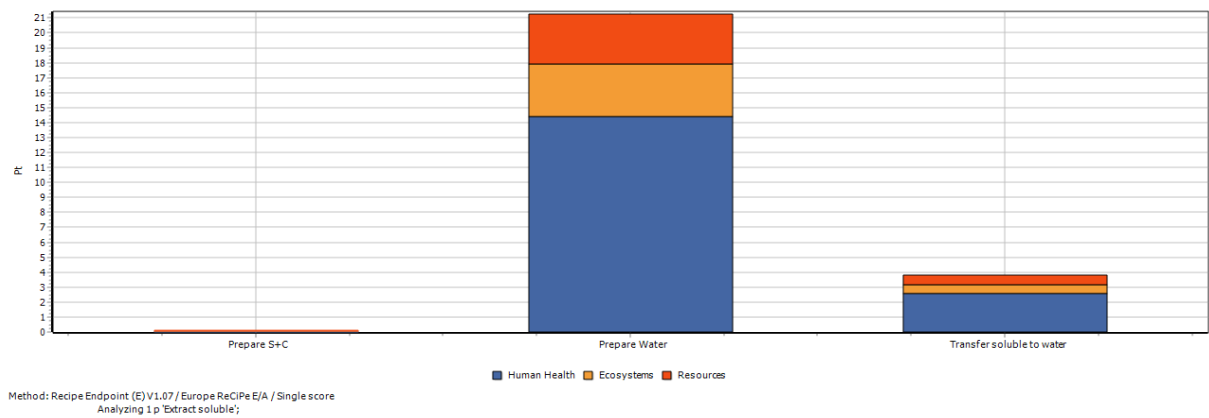


Figure 82: Eco points for Extract Soluble function

The further analysis of the heat water module shows that the impact is due to the materials and manufacturing processes of the components used as well as the energy consumed to operate this module, (refer to the Figure 83).

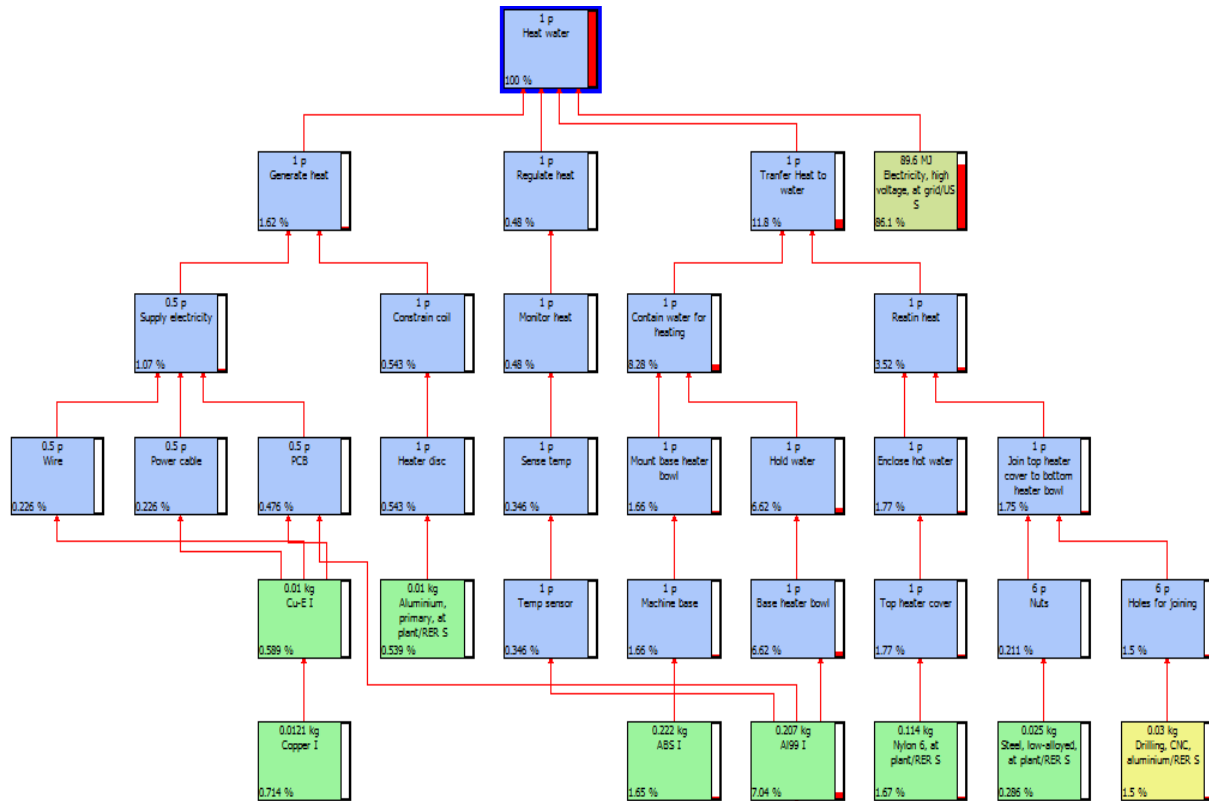


Figure 83: Heat Water module network

6.0 Results and Conclusion

The following section will discuss the outcomes from the implementation of the object- oriented methodology on the Keurig coffee machine.

1] Standardization of Goal and Scope Definition

In conventional LCA different practitioners can use different functional units for the same system, making it difficult to compare the results. In the proposed approach the functionality is defined in an abstract manner along with the relevant reference flows. This sets up the class of systems that are

comparable. For example, the main function of making a coffee is defined as extract soluble to produce beverage. This function and the flows establishes a class under which different coffee brewing technologies like the French press, drip brewing, Keurig single serve brewing, espresso brewing etc., can be compared. As all the technologies of coffee brewing satisfy the same function and have the same transformation they can be compared with the help of the representation in Figure 84. This same abstraction is followed throughout the functional decomposition of the system. Hence as the representation of each building block of the system is standardized, it is easy to drive comparisons at granular levels. Also, the establishment of use parameters has decoupled the consumer behavior from the functional unit definition.

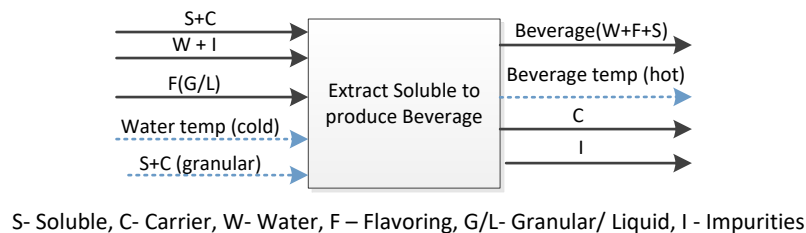


Figure 84: Coffee brewing

The functional decomposition itself acts as a guiding mechanism to establish system boundaries. From this decomposition, the designers can select the functions they want or do not want to implement. The parameters related to the functions will be implemented based on the design decisions made by the designer. This helps to constrain the system boundaries. For example, in the case of Keurig it was decided not to implement the functions related to the mixing of flavoring in the brew and the grinding of the coffee beans. Thus, even though these functions and their parameters were a part of definition they were not a part of the execution. In future, if the designers want to implement these functionalities with the help of technological solutions they can easily add these modules into the analysis and thus expand the system boundaries. Note that in terms of LCA execution this represents a relatively minor effort as compared to executing a specialized LCA that is based on a complete system that implements this added functionality.

2] Easy Generation and Comparison of Use Scenarios-

As stated earlier, consumer behavior has been decoupled from the functional unit definition by developing a set of use parameters that are independent of the technological implementation. One of the important advantages of this approach is that the designers can model changes in the user behavior and analyze impacts of these changes very easily. The relationships between the use parameters, system parameters for the modules and the cumulative damage functions are already established when the system is defined. Hence the changes to the use parameters would drive the changes in the calculations for system parameters and CDF values of the modules. Note that while these relationships can all be established parametrically and can be easily updated, limitations in the SimaPro platform prevented the full demonstration of this.

Consider that the scenario where designer wants to evaluate the impacts of changes in user behavior on the Keurig system. A new high usage scenario, say S1, can be easily modeled as shown in the Table 5.

Table 5: New usage scenario S1

Use Parameter	Average Usage	Scenario S1 High Usage
Quantity of Coffee grinds	1.47 oz	4.5 oz
Quantity of water	26.44 oz	79.5 oz
Temperature of inlet water	68°F	68°F
Quantity of beverage	27.9oz	81 oz
Quantity of beverage per serving	9oz	9oz
Temperature of Beverage	140F	160F
Strength of coffee	1.25%	1.25%
Max TDS (Total dissolved solids in brew)	250ppm	250ppm

Note that if all the rules are defined and the limitations of SimaPro are overcome in a future software platform, the changes in the use parameters would automatically change the system parameters and the CDF calculation/allocation of the modules. This way it would be possible to generate a comparison as shown in Figure 85.

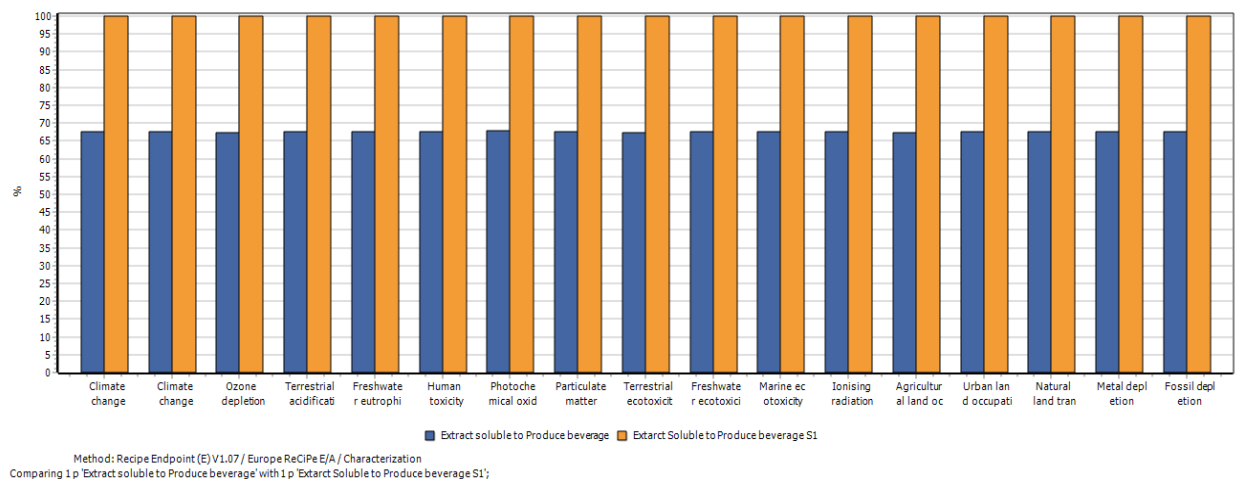


Figure 85: Scenario comparison

The main function 'Extract soluble to produce beverage' for old scenario is compared with the main function 'Extract soluble to produce beverage S1' for new scenario. Note that the above graph is for demonstration purposes only, CDF values of modules have been changed based on judgement. Actual data for CDF calculations and a new software platform will be required for real results. The impacts of usage change can also be evaluated at a granular level. Figure 86 compares change in the impacts of the prepare water function due to change in usage.

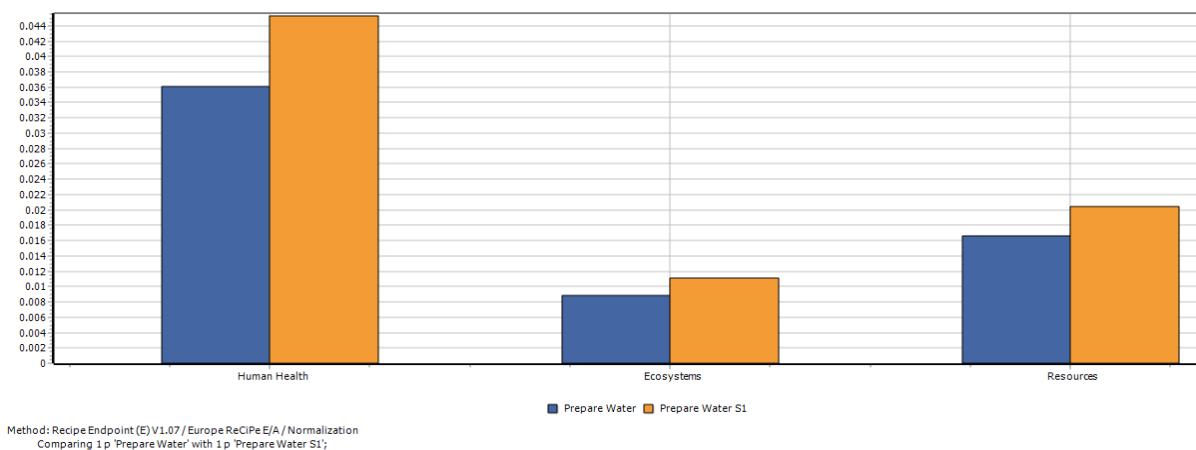


Figure 86: Scenario comparison -Prepare Water

3] Evaluation of alternatives at granular levels leading to reduce data and time requirements

As the representation of the functions and the flows has been standardized at all the levels of the decomposition, alternative technologies and scenarios can be compared at modular levels. The encapsulation and comparison of data at modular levels would lead to reduce data and time requirements, as will be explained below. This approach provides a very detailed structure for investigation. For example, as shown in the Figure 87 the heat water function is the main environmental stress point. The heat water function is defined in the decomposition in a generalized manner so that any heating technology can be compared under the same class. The information required to make technological choices for satisfying this function is the quantity of water to be heated and the temperature to which it needs to be heated. This information is directly obtained from the use parameters defined. Alternate technologies like electrical heating, Solar heating, gas heating, ultrasonic heating etc., can be compared at this level. The structure of the alternate solution chosen can then be mapped to the heat water function without making any changes to the other part of the system. The same approach can be followed for all the other modules. This ability to make comparisons at a granular level without triggering changes to the other parts of the system would help to reduce data and time requirement. Figure 88 shows the demonstration of how existing heat water system compares with solar and gas heating systems for the same usage.

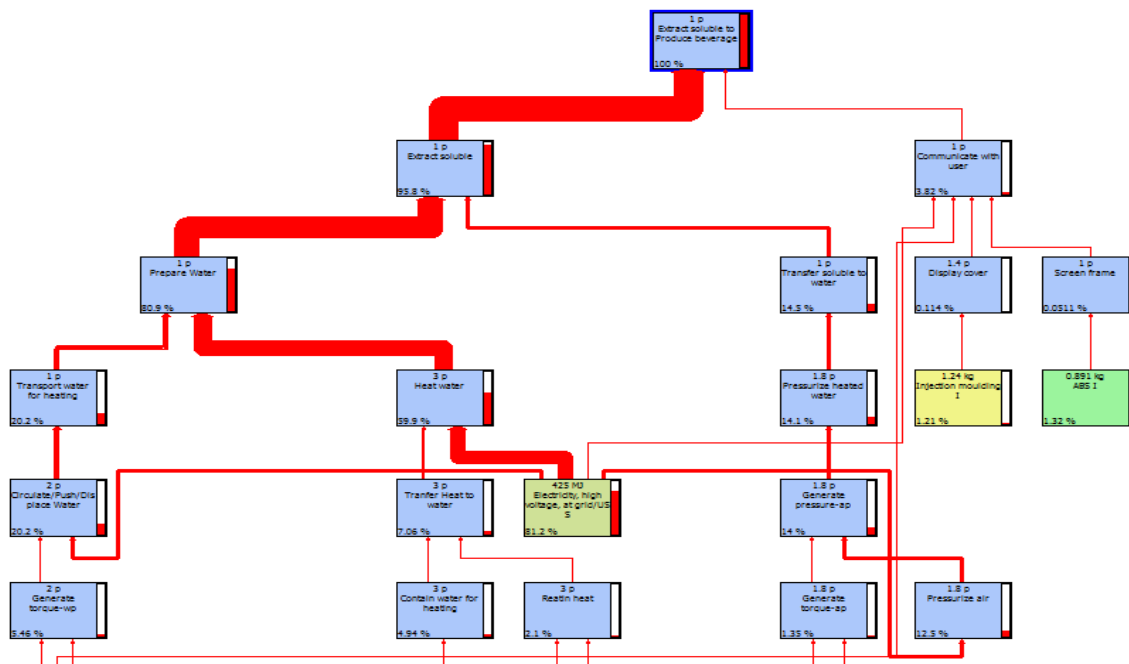


Figure 87: Impact Network

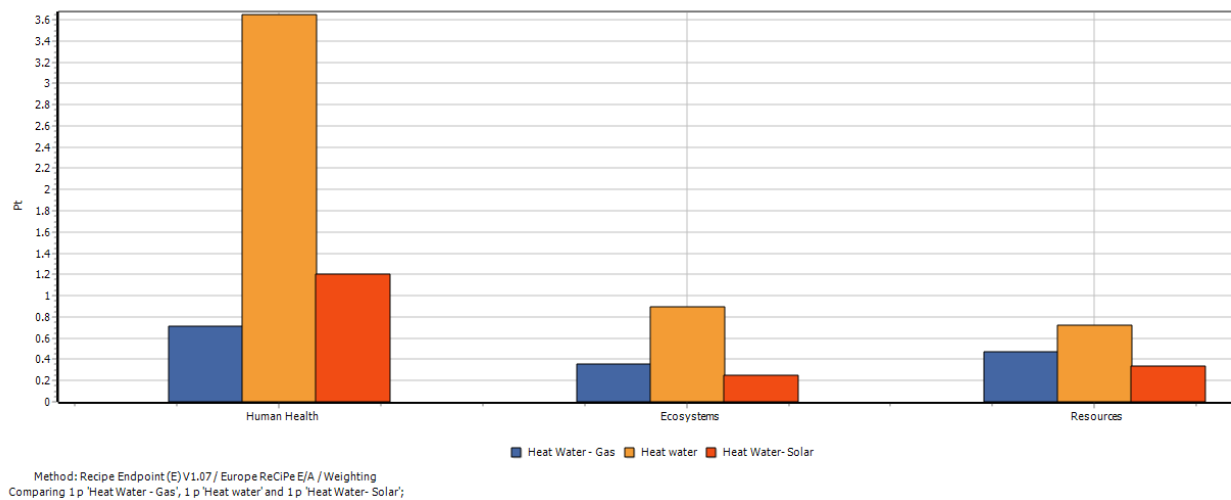


Figure 88: Comparison Heat water solutions

Below, some of the other foreseeable benefits of this approach will be summarized:

A) Reusability – The ability of the modules to be used in different applications. Modules or functional blocks that are developed can be reused and integrated into a different application. For example, ‘contain

water' is a very generic functional block. There are various other applications like humidifiers, rice cooker, water filters etc. in which this same module is necessary to implement the functionality. Once the knowledge of environmental impact of this building block is obtained, and more importantly, the relationships that have been developed, this same knowledge can be reused for other systems. The system parameters and the CDF for the blocks can be easily derived from the use scenario of the new system in which one wants to reuse the module. In order to accomplish this, however, the definition of the functional transformation and the systems parameters becomes critical. This is why it is important that the same processes and rigor used to define functional transformations at higher levels needs to be applied at the lower levels because this establishes the class of systems that can implement these functions. Thus, the more general the function and parameter definitions, the greater the reusability of the modules are.

B] Compatibility- The ease of combining, adding /subtracting elements. By leveraging the insight is A], adding modules to the existing decomposition becomes an easier task, provided that broad view of the functions required to completely execute the desired functional transformations are considered. In the case of the coffee maker, it was necessary to recognize that grinding beans and adding flavorings are part of the process of making the beverage regardless of whether or not the existing system performed this function.

Thus, the process in effect defines the require transformation and reference flows that are required for subsystems of that class, and leaves the “hooks” in place to add it in the future. Once this is done the module can be easily integrated into a given decomposition. Expanding and contracting the system boundaries a much more straight-forward process.

C] Efficiency- The formalization and encapsulation of knowledge at granular levels. The system can be improved at various levels of granularity. Changes made to the modules do not trigger significant changes in other parts of the system. Multiple technologies can be modeled and compared

D] Ease of use- The modeling approach is compatible with design activities. Multiple scenarios can be generated and compared just by changing the values of the use parameters. Functional analysis is an important tool used by designers during the conceptual development phase. Hence it is very easy for designers to think in terms of functions rather than the structural details during this phase. Our approach provides a structure for system level investigation. Quantifiable parameters are used to model changes in the system as well as black box modeling is used to represent the system. Hence the LCA approach that is developed is feasible to execute in a meaningful way with design activities.

This chapter will conclude by revisiting the objectives and assessing how they were achieved. In chapter 3, the stated objectives were:

- Define a methodology to systematically apply the framework to a simple product
- Further our understanding of the implementation details and challenges of this approach
- Apply the framework to a more complex electro-mechanical system
- Suggest improvements to the methodology

The standardized framework for the integration of functional analysis in LCA developed by Esterman, et al. (2012a) was applied to the can opener. A methodology to create a detailed hierarchical decomposition, to identify reference flows and define use and system parameters was explained. The completeness of the can opener functional decomposition was verified using a bottoms-up reverse engineering approach ‘subtract and operate’. The implementation details of the approach were uncovered by generating and analyzing the environmental impacts of the can opener function-structure in Simapro. Also, the need for a more sophisticated, object-oriented software platform was presented to tackle the limitations of the current software. Further, the same methodology was implemented on a Keurig 2.0 coffee machine. Two new concepts namely the ‘reversible functions’ and ‘feature level addition’ were introduced to deal with the allocation challenges for a complex system. A ‘cradle to grave’ impact evaluation of the coffee machine lifecycle was performed in Simapro. The results were analyzed to drive conclusions and

understand the benefits of the approach presented. The following section presents some of the opportunities to improve the methodology.

7.0 Future Work

In this section, various opportunities for future work to improve and consolidate the approach are discussed.

1] End of life strategies-

One of the important aspect of LCA is the ‘Cradle to Grave’ approach, hence evaluating the impacts related to the disposal of the system is of great importance. Various end-of-life scenarios can be constructed like landfill, remanufacturing, recycling, reuse etc. Different components and sub systems have different end of life capabilities, for example some components can be recycled while others need to be disposed. Some sub systems can even be disassembled from the main system and reused or remanufactured after the end of life. These decisions are usually very specific to the technology employed and product architecture used. Integration of disposal scenarios into the functional model should be explored in the future work. Some guidance for approaching this problem can be found in Rose (2000). Her research looks at the methodologies that can be used to determine the end of life strategies based on characteristics of the product. According to the researcher, the important characteristics of product that influence End of life decisions are “wear-out life, technology cycle, level of integration, number of parts, design cycle and reason for redesign”. Three important questions that should be answered as a part of future work are-

- Can the end of life strategies be classified based of the functions?
- How can the controllable parameters that affect EOL strategies during the design phase be integrated into the object-oriented framework?
- What is the influence of user behavior (use scenarios) on the EOL strategies?

It should be noted that an important observation that was made during the inclusion of features during the mapping of components to the functions is that as long as activities are being tracked, this mapping process is fairly straight-forward. So as end-of-life dispositions are considered, it becomes easy to think about the activities associated with disassembly and disposition, which maps into the components, which in turn map into the functions. So, the mechanism is there to establish these linkages.

2] Development of interface parameters and uncertainty analysis

While verifying the proposed flow down of information hierarchically some exceptions at lower level of the architecture were found. One such exception of the circulate/push water is explained in the section 5.2.2. One of the approach to deal with this issue is to develop a set of interfacing parameters for classes through which the information can be shared. Another opportunity is to accommodate uncertainty in the approach. When the function- structure model is initially developed and parameters are defined, the knowledge of the practitioner may be imperfect. Function structure analysis is an iterative approach, hence the knowledge about the system becomes more complete with time. Also, the data quality may improve with time. Hence including uncertainty analysis would be helpful.

3] Clustering of functions to form independent modules-

Currently the CDF values are calculated for the stand alone sub-assemblies identified from already existing structure of the Keurig machine. Identification of modules based on structure is a limitation of this implementation. It is important that these modules be identified from the functional space itself in order to make the definition module as independent of the implementation of the module as possible. Different ways to cluster modules based on flows and functionality should be explored as a part of future work. One such promising approach is explained below-

Holttä et al., (2003) develop an algorithm that can help to group functions from a functional decomposition to form independent modules. The authors propose a five-step methodology which consists of developing a functional decomposition, characterizing the functions, screening of functions for

potential grouping, calculation of a distance matrix between all the functions and finally the building of a dendrogram. Some of the important strengths of this approach are-

- The focus of the approach is on flows and not only the functions, this enables the use of ratio scales.
- Metrix space with a distance function is developed which is based on flow characteristics of the functions.
- The flexible flow method used and the algorithm is executable in a computer.

The future work should focus on how can this or a similar approach can be implemented in the object-oriented framework.

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Appendix A

Keurig 2.0 Bill of Material

System Name				Keurig K 2.0				
Number of Total Parts in Complete System				160				
Major Sub Assemblies				15				
Total Weight (grams)				3140.5				
Total Number of Unique Parts in Complete System				111				
Major Sub Assemblies	2nd Order Sub Assemblies	3rd Order Sub Assemblies	Part	Quantity	Material	Function	Part Weight	Manufacturing Processes Used
Water reservoir Assembly	Tank		Tank casing	1	PS	Contain W+I	306	INJECTION MOLDING
			Screws	3	MS	Fasten filter attachment with tank casing	0.5	DRAWING
			Filter attachment	1	PP	Hold filter	1	INJECTION MOLDING
			Plunger	1	PP	Regulate water from tank to the heater	0.5	INJECTION MOLDING
			Spring	1	MS	Control Plunger movement, engage, disengage	0.5	WIRE DRAWING
			Top Lid	1	PS	Prevent W+I contact with external environment	58	INJECTION MOLDING
	Water Filter		Filter element			Separate W from I		
			Upper filter holder	1	ABS	Indicate Filter lifespan	4	

			Lower filter holder	1	ABS	Mount filter element	6	INJECTION MOLDING
			Filter Body	1	ABS	Hold filter assembly	18	INJECTION MOLDING
Front panel Assy								
			Front panel	1	ABS	ENCLOSE ASSEMBLY	116	INJECTION MOLDING
			Screws	2	MS	Fasten front panel with the	4	DRAWING
Back Panel								
			Base	1	PP	Mount sub-assemblies	300	INJECTION MOLDING
			Rubber bush	2		Absorb vibrations		
			Reservoir Support	1	PP	Enclose assembly/ Attach tank casing	104	INJECTION MOLDING
Drip tray Assembly			Top connector	1		Connect brew head to reservoir support		
			Drip tray cover	1	PP	Secure cup/ cover the tray base/ Guide excess beverage	20	INJECTION MOLDING
			Drip tray base	1	PP	Collect excess beverage/ Secure carafe	64	INJECTION MOLDING
K cup holder assembly	Bottom needle assembly							
			Coil Spring	1	MS	Control needle housing motion	0.5	WIRE DRAWING
			Lower piercing Needle	1	MS	PIERCE K CUP (guide S+W)	1.5	DRAWING & MACHINING
			Needle Housing	1	PP	HOLD needle	3.9	INJECTION MOLDING

			Bush Rubber	1	NEOPRENE	Mount needle housing/ Avoid friction	0.1	MOLDING
	K cup holder							
			Gripper	1	PP	HOLD K CUP/ dispense S+W	14	INJECTION MOLDING
			Grip Holder	1	PPE PS GF	Hold gripper/dispense S+W/ holds bottom piercing needle	44	INJECTION MOLDING
			Holder Casing	1	PP	Join to bottom jaw body	32	INJECTION MOLDING
Dispense r Guide	Dispenser guide			1	PP	Transport S+W	22	INJECTION MOLDING
Top Housing								
	Handle Assembly							
			Handle	1	ABS	ENABLE OPENING AND CLOSING OF K CUP HOLDER	72	INJECTION MOLDING
			Handle cover	1	PP	Enable assess to k cup holder	24	INJECTION MOLDING
	Bottom Jaw							
			Bottom Jaw Body	1	PC GF	Hold safety switch/ support holder assembly/ Mount top jaw	75	INJECTION MOLDING
			Safety Switch	1	PP	SAFETY (transmit jaw closed signal)	4	INJECTION MOLDING
			Pin	4	MS	PROVIDES ROTATIONAL DEGREE OF FREEDOM/ enable opening and closing of k cup holder.	1	PRESS

							44	
	Display Assembly		Screen Frame	1	ABS	Hold screen		
			Screws	4	MS	JOIN screen frame to upper mounting frame	0.8	DRAWING
			Display PCB	1		Mechanical support/Electrical connections	3	
			Display Screen	1	ABS	Accept user input/ Display information	41	MOLDING
		Display Cover						
			Brew Button	1	PP	ACCEPT user input	2	INJECTION MOLDING
			Rubber Seal	2	NEOPRENE	Control bottom motion	2	INJECTION MOLDING
			Display Cover	1	ABS	Enclose display assembly	42	INJECTION MOLDING
	Top Jaw							
		DRM Assembly	Electrical Wiring	1		Conduct electric current	3	
			IR Lights	3			2	
			Lens	1	PS		0.5	INJECTION MOLDING
			Upper Mounting frame	1	ABS	HOLD DRM ASSEMBLY	41.5	INJECTION MOLDING
			Circuit Board	1		MOUNTING BOARD	0.5	
			Wire Holder	1	PP	HOLD AND CONTAIN WIRES	2	INJECTION MOLDING

			See Through Plastic	1	PS	VISIBILITY	0.5	INJECTION MOLDING
		Top Needle Assembly					54	
			Orifice Needle	1	MS	PIERCE K CUP/ transport heated water	2	MACHINING
			Upper piercing Needle	1	MS	PIERCE K CUP	2	MACHINING
			Rubber Bush	1	NEOPRENE	SUPPORT	0.5	MOLDING
			Top Needle frame	1	PC GF	HOLD NEEDLES/ enables opening closing of k cup holder	49.5	INJECTION MOLDING
Brew Head Assembly								
			Brew Head	1	ABS	HOLD K CUP HOLDER ASSEMBLY	266	INJECTION MOLDING
			Screw	3	MS	JOIN	4	DRAWING
Air Pack			Valve	1	PP	REGULATE WATER FLOW	6	INJECTION MOLDING
			pipe	1		GUIDE WATER	4	
	Air pump assembly					Transport heated water/ Pressurize heated water		
			Air pump Motor	1		GENERATE TORQUE	52	
			Coupler	1			1	INJECTION MOLDING

			Rotor	1	PP		1	INJECTION MOLDING
			Mounting plate	1	MS		2	MACHINING
			Diaphragm	1	NEOPRENE		1	MOLDING
			Diaphragm holder	1	ABS		2	INJECTION MOLDING
			Housing	1	ABS		4	INJECTION MOLDING
			Outlet chamber	1	ABS		2	INJECTION MOLDING
			chamber screws	2	MS		1	DRAWING
			mounting screws	3	MS		1	DRAWING
			Mounting frame	1	PP		58	INJECTION MOLDING
	Valve assembly					Regulate water flow/ regulate air flow		
			Screw	3	MS	JOIN	1	DRAWING
			Pipe	1		GUIDE WATER	6	
			Valve Body	1	PP	SUPPORT	6	INJECTION MOLDING
			Plunger	1	PP	REGULATE WATER	0.5	INJECTION MOLDING
			Spring	1	MS	MAINTAIN CONTACT	0.5	DRAWING
			Holder	1	PP	HOLD	0.5	INJECTION MOLDING
			Pipe and ring	1	PP	GUIDE	8	INJECTION MOLDING

			Pipe connector	1	PP	CONNECT	8	INJECTION MOLDING
Water Pack								
			Water pump Motor	1		Generate torque	162	
			Screws	2	MS		2	
	Pump outlet inlet chamber		Chamber	1	POM		10	DRAWING
			Washer Screws	4	MS		2.2	MACHINING
			Screws	4	MS		1	INJECTION MOLDING
			Cap	1	POM		6	INJECTION MOLDING
			inlet plunger	1	PP		1	INJECTION MOLDING
			O ring	4	NEOPRENE		1	INJECTION MOLDING
			outlet plunger	1	PP		1	INJECTION MOLDING
			Spring	2			2	
				1	POM		28	INJECTION MOLDING
	Pump Chamber							
			Main housing	1	POM			INJECTION MOLDING
			Diaphragm	1	NEOPRENE		2	
			Piston Guide	1	POM		10	INJECTION MOLDING
	Water Pump							
			Rack	1	STEEL		10	MILLING
			Pinion shaft	1	PA		8	INJECTION MOLDING
			Cover	1	POM		14	INJECTION MOLDING

			Crank shaft	1	PA		7	INJECTION MOLDING
			Piston	1	PA		7	INJECTION MOLDING
			Connecting rod	1	PA		10	INJECTION MOLDING
			screw	1	STEEL		2	
			Pump casing	1	POM		60	INJECTION MOLDING
								INJECTION MOLDING
			Bearing	1	BRASS		2	MACHINING
			Circlips	4	MS		0.5	PRESS
Heater Assembly						HEAT WATER		
			Screws	8	MS	Join Top cover to base heater	8	
			Nut	5	MS	Join Top cover to base heater	1	DRAWING
			Top cover	1	SPS	Contain water for heating	114	PRESS
			Sensor clip	1	MS	Hold Sensor	10	INJECTION MOLDING
			Base Heater	1	ALUMINUM	Hold water for heating/ Transfer heat to water	192	DEEP DRAWING
			Pipe clip	1	MS	Hold pipe	1	PRESS
			Temp Sensor	1		Sense temperature	10	
			Pipe	1		Transport water	8	INJECTION MOLDING
			Wire clip	1	PP	Hold Sensor wire	1	
Main PCB				1			180	
			PCB Cover	1	CARDBOARD	Support PCB	12	PRESS
Machine Base Assy				1		HOLD MACHINE ASSEMBLY		
			Machine Base	1	ABS	Mount subassemblies	222	INJECTION MOLDING

		Power cable support	1	ABS	Hold power cable	2	INJECTION MOLDING
		Screw	1	MS		2	DRAWING
		Ethernet Port	1	ABS	Allow remote monitoring of product	2	INJECTION MOLDING
		Bottom bush	2	NEOPRENE	Absorb vibration	2	MOLDING

Appendix B

Functional decomposition

